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DESIGN OF A MICROMINIATURE PRESSURE TRANSDUCER

Interim Report on Task 9R38-11-009-17

Contract AF33(616)-6814

June 1961

prepared by:

ROSEMOUNT AERONAUTICAL LABORATORIES
University of Minnesota

for:
FLIGHT DYNAMICS LABORATORY
Wright Air Development Division
Air Research and Development Command

under MIPR R-59-13-TC-RE with:
U. S. ARMY TRANSPORTATION RESEARCH COMMAND

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Fort Eustis, Virginia

TCREC-ADS 9R38-11-009-17

SUBJECT: Project 9R38-11-009-17, Miniature Pressure Transducers

TO: See Distribution List

1. The report contained herein was prepared by Rosemount Aeronautical Laboratory for the Wright Air Development Division (WADD), Air Research and Development Command, U. S. Air Force, in accordance with the stipulations of MIPR R-59-13-TC-RE initiated by United States Army Transportation Research Command.

2. The conclusions made by the contractor are concurred in by this Command. Based on these conclusions, recommendations are being made that efforts be concentrated toward perfecting a miniature pressure transducer. This recommendation reflects the views of this Command and not necessarily the Chief of Transportation or the Department of the Army.

3. The transducers involved in this investigation plus other transducers being investigated by the U. S. Air Force were evaluated by WADD. A report on the results of the evaluation tests will be published in June 1961.

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DESIGN OF A MICROMINIATURE PRESSURE TRANSDUCER

Prepared by

Rosemount Aeronautical Laboratories

University of Minnesota

Minneapolis, Minnesota

for

Flight Dynamics Laboratory (Project 1367, Task 14037)
Wright Air Development Division
Air Research and Development Command

Wright-Patterson Air Force Base, Ohio

under MIPR R-59-13-TC-RE with

U. S. ARMY TRANSPORTATION RESEARCH COMMAND
Fort Eustis, Virginia

FOREWORD

This report contains the results of an investigation carried out for the Wright Air Development Division, Air Research and Development Command of the U. S. Air Force under contract number AF 33(616)-6814. The program was under the technical supervision of the Structures Branch, Flight Dynamics Laboratory of WADD. The authors wish to acknowledge the technical assistance received from Messrs. Richard W. Bachman and George W. Riess, the project monitors for WADD.

The fabrication of two "Baroducer" miniature pressure transducers was carried out under the above contract on a subcontract basis by the International Dynamics Corporation, Somerville, Massachusetts. The authors wish to express their appreciation to Mr. William A. Curby, Research Director of that company, for his cooperation in this subcontract work. Test data on a semiconductor type of pressure transducer was provided under the above contract on a subcontract basis by the Giannini Controls Corporation, Duarte, California. The authors are grateful to Dr. Alex Moncrief-Yeates for his assistance and cooperation in providing this data.

The authors wish also to acknowledge the assistance of Mr. Fred Aldrich of the Technology Instrument Corporation, Acton, Massachusetts for his helpful suggestions in the field of vacuum deposition technology, Mr. Lyall K. Smith of the Rosemount Aeronautical Laboratories for his indispensable aid in the preparation of transducer models, and Mrs. Janet R. Hammer for her assistance in the preparation of the final report.

ABSTRACT

The problem of designing an accurate microminiature pressure transducer suitable for bonding to a vehicle surface exposed to a moving airstream has been reviewed in detail. A summary of the present state-of-the-art in the design of pressure transducers suitable for miniaturization is presented. A detailed discussion of newly evolved pressure measuring techniques and adaptations of proven techniques considered feasible for the above application is given.

Of the pressure measuring techniques investigated, two were chosen by the sponsoring agency to receive further design and developmental work. A design study of the use of the diode principle in the design of a miniature pressure transducer is presented. Details of the development of a diaphragm type variable resistance pressure transducer of rather unique design are presented along with calibration data obtained on a scaled-up model of the transducer. The conclusion is reached that this transducer, referred to as the resistance-shunting pressure transducer in the text, shows good promise for the above application due to its high sensitivity, rapid response and simplicity of construction. Further development is suggested to achieve linearity of output and temperature insensitivity.

An analysis of the calibration data obtained on a scaled-up model of the resistance-shunting pressure transducer is presented which illustrates that linearity and higher overall sensitivity can be obtained for the present design by an appropriate shaping of the transducer's resistive element.

PUBLICATION REVIEW

This report has been reviewed and is approved.

FOR THE COMMANDER:

/s/ John P. Taylor
JOHN P. TAYLOR
Colonel, USAF
Chief, Flight Dynamics Laboratory

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1. INTRODUCTION

The design and development of a microminiature pressure transducer suitable for bonding to aircraft surfaces immersed in a moving airstream, undertaken under contract number AF 33 (616)-6814 for the Wright Air Development Division,* is herein reported. The program was divided into two phases; Phase 1 consisted of a study phase while Phase 2 consisted of the final design and development of the two most promising transducers evolved from the study phase.

The aim of the study phase of the program was to investigate all possible techniques of measuring nonsteady pressure airloads bearing in mind the specific requirements of the sponsoring agency. In order to gain background information on past and present methods of measuring unsteady pressure airloads, the usual scientific literature and also the experience of instrument manufacturers were drawn upon. The specific design requirements of the sponsoring agency borne in mind during the study phase are summarized as follows:

Synopsis of Design Requirements:

Size and Weight - Minimum size and weight are desired. Maximum thickness 0.015"; maximum width 0.25"; maximum depth 0.50".

Method of Attachment - The transducer shall be flush mounted on the vehicle surface. Method of attachment shall be such that no alteration of the vehicle structure is required and the structural integrity of the surface is preserved.

Power Consumption - Minimum power consumption is desired.

Temperature Range - The transducer must be capable of operation over the temperature range of -55°C to +100°C.

Accuracy - The transducer accuracy should be at least ±1% of full scale under any combination of the following conditions:

a) temperature,
b) linearity,
c) hysteresis effects, and
d) acceleration.

*This report was prepared under MIPR R-59-13-TC-RE with the U. S. Army Transportation Research Command, Fort Eustis, Virginia.

Acceleration - The transducer must be able to withstand accelerations of 30 g's normal to the plane of measurement and 800 g's parallel to the plane of measurement.

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Internal Impedance - A maximum of 500 ohms internal impedance is desired.

Mach Number Range - The transducer must be capable of operating at Mach numbers through one.

Phase Shift - The phase shift shall not exceed 5° over the flat frequency response range of the transducer.

Environmental Specifications - Environmental testing will be to MIL-E-005272B except that Exhibit A of the subject contract will have precedence over said specifications.

Range - The pressure range of the transducer shall be ±15 psi from ambient pressures of 0 to 15 psia. Either a differential or absolute pressure transducer is acceptable.

Safety Factor - A minimum safety factor of 50% pressure overload is desired.

Frequency Response - The transducer shall have a flat frequency response in two ranges, 0 to 1000 cps and 0 to 10 kc. In either range, the device shall have a flat frequency response to a step input pressure. The transducer must be capable of measuring both steady state and slowly varying pressures as well as high frequency inputs. Separate designs may be applied to each range if necessary or desirable.

Power Supply - Electrical power for the system may be either AC or DC, preferable 400 cycle, 115 volt AC or nominal 25 volt DC. Internally powered, self powered, or battery powered units should be considered.

Readout Equipment - Readout equipment is optional so long as output is readable and lends itself to recording on available commercial recording devices.

During Phase 1 of the program, effort was divided into the following major categories: review of scientific literature, inquiries to commercial companies, travel to several commercial companies, and evolution of new techniques and modification of existing techniques. The above divisions of effort were closely interrelated. In many cases technical references triggered ideas for new techniques or modification of existing techniques. Consideration of these new techniques frequently led back into the scientific literature and prompted examination of further references.

Some of the basic means of measuring pressure which have been utilized in the past are as follows:

1) The deformation of a structure when a pressure load is applied; 2) The unbalance of a fluid in a manometer when pressure is applied; 3) The rate at which heat is lost from a heated surface, e. g., the Pirani gage; 4) The piezoelectrical effect; 5) The change in natural frequency of a piezoelectrical crystal when pressure is applied; 6) The electrical conductivity of a gas, e. g., the ionization vacuum gage; 7) The change in resistance of a wire due to the change in cross sectional area (this technique has been used at very high pressures); 8) The streaming potential developed by a polar liquid flowing through a porous plug; 9) The dead weight, free piston type gage; 10) The volume change of a gas undergoing compression or expansion (isothermal or adiabatic); 11) The hypsometer, the output of which depends on the relationship between boiling temperature and ambient pressure.

It is also possible to determine pressure by a simultaneous measurement of density and temperature or by a measurement of density at a controlled constant temperature. Several examples of density measuring devices are: 1) The radioactive ionization gage which essentially uses radioactive particles to ionize the gas in a chamber and collects the ion particles to produce a current proportional to the density in the chamber; 2) The electrical corona discharge gage which relates the passage of electric current through a gas as a result of high potential difference to the density of the gas; 3) The damping of a vibrating wire or diaphragm as a result of the gas present; 4) The attenuation of sound waves when passed through the test gas; 5) The attenuation of X-rays when passed through the test gas; 6) The absorption of an electron beam when passed through the test gas.

Although in the study phase all of the basic techniques mentioned above were considered, the general conclusion reached was that for the present application the first technique mentioned showed the most promise, i.e., the deformation of a structure when a pressure load is applied. In general the other techniques mentioned have one or more serious disadvantages which appear to render their use impractical for the present application. A general discussion of the more serious disadvantages of these techniques follows; a more detailed discussion of some of these techniques is presented in other sections of this report.

Disadvantages of the fluid manometer are sensitivity to orientation, low frequency response, and sensitivity to acceleration effects. Devices relying on the transfer of heat are inherently slow in frequency response. Piezoelectric crystals possess high temperature sensitivity. In addition, measurement of steady state pressures using the piezoelectric effect is difficult due to charge leakage effects. Transducers utilizing the streaming potential developed by a polar liquid flowing through a porous plug are unable by their nature to measure steady state pressure levels. In addition to specific disadvantages of the several density measuring techniques mentioned above, these techniques in general present the difficulty of requiring a temperature measurement in order to deduce pressure from the equation of state. Since this would require measuring temperature with a very high frequency response device, difficulties posed by such a system would be most serious.

Techniques utilizing the deformation of a structure with pressure load, in particular the deflection of a diaphragm with pressure, were concluded to have the greatest promise for the desired application for several basic reasons. A flush, flat or spherical segment, diaphragm transducer of the size desired has an inherently high frequency response. With moderate care in design the effects of acceleration and vibration can be made almost negligible. Temperature effects can be minimized to some extent by careful choice of material and/or fabrication techniques. And finally, a great variety of methods are available for converting the diaphragm deflection to an electrical output. The two pressure transducer types investigated under Phase 2 of the program and reported in sections 6 and 7 are both flush diaphragm types.

2. SUMMARY OF THE PRESENT STATE-OF-THE-ART IN PRESSURE TRANSDUCER DESIGN

2.1 Literature Survey

The initial background work on the literature survey was greatly expedited by the use of reference 1, which is an exceptionally complete bibliography and index on pressure measurement covering work done prior to May, 1954. During the study phase of the contract, all of the references contained in that bibliography, which appeared to be at all applicable, were investigated. To avoid duplication, references contained in that bibliography will not be contained in the list of references of this report unless judged by the authors to be particularly significant.

The literature survey uncovered a number of relatively general works on instrumentation which proved very valuable both from the standpoint of presenting countless basic ideas for the measurement of pressure and the evaluation of performance of pressure transducers and from the standpoint of presenting many additional references on pressure measurement. Reference 2 presents a great number of basic schemes for measuring physical quantities by electrical methods. This reference was invaluable from a standpoint of triggering new ideas for combining several basic schemes of transduction. Reference 3 is a similar work presenting a variety of methods of measuring mechanical or physical quantities by electrical methods. This reference places more emphasis on electric circuit design. Reference 4 is a general work on pressure and temperature instrumentation which discusses the state-of-the-art in instruments commercially available in this country at the time of its publication, 1947. Reference 5 is another general reference on instrumentation stressing the state-of-the-art in instrumentation commerically available in Great Britain at the time of its publication, 1953. A very complete presentation of the fundamentals of instrument engineering and the design and analysis of various types of instrument systems is presented in reference 6. This last reference was particularly useful during the final design work carried out under Phase 2 of the program.

To include a discussion of all references investigated during the program would be, in the opinion of the authors, not only extremely time consuming but, in addition, grossly inefficient. As stated in section 1, diaphragm type transducers in general showed the most promise for the present application. As a result, the bulk of the following discussion of references deals with transducers of this type. These can generally be classified by the transduction technique employed as follows: 1) variable resistance, 2) variable capacitance, 3) piezoelectric effect, 4) variable inductance, and 5) nulling techniques.

2.1.1 Variable Resistance Techniques

Reference 7 describes a literature survey and experimental program conducted by the Cook Research Laboratories, Chicago, Ill., in the area of variable resistance pressure transducers. The properties of diaphragm materials, including metals, glass, fused quartz, plastic, rubber, and others, are discussed. Operating characteristics are presented for a number of variable resistance transduction techniques including the moving contact type, the strained element type (metal wire strain gage, conductive rubber and conductive plastic strain gages, and vacuum deposited thin metal films), and the variable contact spring type. Of particular interest was a section describing fabrication of semiconductive, pressure sensitive plastic sheets by introduction and orientation of conducting chains of carbon particles in the plastic matrix. The resistance instability problems encountered in this latter technique are discussed further in section 3.2.

Reference 8 describes a pressure transducer in which diaphragm deflection is sensed by the aid of a cantilevered element attached to the diaphragm. The deflection of the diaphragm causes bending of the cantilevered beam, which in turn is sensed by strain gages bonded to the beam. Calculations are presented for obtaining the maximum sensitivity of the diaphragm by theoretically determining the optimum cantilever dimensions. The technique of incorporating either two or four resistance strain gages as active bridge arms in order to minimize changes in output due to temperature is discussed. It is pointed out that for bonded strain gage type diaphragm transducers the effect of temperature variation across the diaphragm is accentuated by the heating of the diaphragm due to the electrical power dissipated in the gage, by the mechanical effect of the gage itself on the diaphragm, and by the effects of expansion and contraction of the transducer body with environmental temperature changes. Although this reference contains interesting information on problems associated with strain gage diaphragm transducers, the specific transducer described would not lend itself readily to miniaturization.

Another strain gage type of pressure transducer is described in reference 9. This small pressure cell is approximately 1" in diameter and 1/4" thick. The diaphragm itself is dish-shaped with strain gages cemented to either side in order to minimize errors due to creep and hysteresis. Temperature gradients are reduced by protecting the diaphragm with a perforated metal cover. The sensitivity of the transducer is 295 microvolts/psi when an 11.8 mil thick Beryllium-copper diaphragm and a six-volt power supply are used. Accuracy under these conditions is approximately 0.5% of full scale from 0 to 7 psi including the effects of linearity. Sensitivity can be increased to 2.25×10^3 microvolts/psi by using a 4 mil diaphragm; however, accuracy then decreases to approximately 1% of full scale.

Reference 10 discusses in general the problem of measurement of dynamic pressures in rocket chambers, shock tubes, and jet exhausts. A water cooled diaphragm type strain gage transducer developed by the author of that reference and used in the analysis of pressure propagation in shock tubes is described in detail. The transducer is basically a flush diaphragm type in which a deflection of the diaphragm compresses a strain tube instrumented with mutually crossed unbonded strain gage windings. Temperature compensation of the device is excellent and liquid cooling allows operation for short duration up to approximately 6000°F. A comprehensive list of references is included in reference 10.

Reference 11 describes a flush diaphragm pressure transducer, designed by the Ames Aeronautical Laboratory of NASA, which utilizes a strain gage type element. To increase the linearity, the diaphragm is initially strained before attachment to the diaphragm rim. This transducer has been constructed in diameters of 1/2" and 1/4", the smaller transducer having a 5000 cps natural frequency diaphragm designed for measuring pressure differentials up to 5 psi. These transducers are designed primarily for measurement of dynamic pressures and no temperature compensation is provided.

A pressure transducer which utilizes a catenary flush mounted diaphragm acting upon a thin wall steel strain tube is discussed in reference 12. The strain tube is instrumented with two strain gages, one oriented longitudinally on the tube and the other circumferentially. Compression of the strain tube due to the action of the diaphragm causes a decrease in resistance of the longitudinal strain gage and an increase in resistance of the circumferential strain gage. By using the two strain gages as two active arms of a Wheatstone bridge circuit, temperature compensation is achieved. This device was designed for measurement of extremely high pressures with very high frequency response. The full scale pressure range is 60,000 psi while the resonant frequency of the diaphragm-strain tube combination is approximately 45 kc.

For most commercially available strain gages the gage factor, which is defined as the percentage change in resistance for a given strain, is approximately 2. Reference 13 discusses a strain gage constructed of semiconductor material which has a gage factor of 175 and will very shortly be commercially available. Unfortunately this several order of magnitude increase in output is gained at the expense of high internal impedance and considerably greater temperature sensitivity.

2.1.2 Variable Capacitance Techniques

Recent work by the Ames Aeronautical Laboratory of NASA in the development of capacitance type pressure transducers is discussed in reference 14. This reference points out two of the principle advantages of the diaphragm type variable capacitance transducer, simplicity of mechanical construction and small internal heat generation. These advantages contribute to the inherent high frequency response and low thermal instability of these devices. Some of the more pertinent design features of the transducers discussed in reference 14 are their spot welded diaphragms, use of air as a dielectric, use of a conducting gold film for the stationary capacitor plate, and use of a well shielded center electrode to reduce leakage and stray capacitance effects. Flush diaphragm transducers of this type have been constructed with an outside diameter as small as 0.12", a diaphragm thickness of approximately 0.0005", and a range as low as ±1 psi. Overall thickness of these transducers is of the same order of magnitude as the diameter, since they were designed to be flush mounted in models or in wind tunnel walls with the body of the transducer recessed in the wall. Their chief disadvantage is the problem of stray capacitance in the transducer leads, requiring that extreme care be taken in electrical shielding and in the design of the electrical circuitry.

A very high frequency response, high pressure, variable capacitance pressure transducer discussed in reference 14 uses as dielectric material a solid sheet of nylon approximately 0.003" thick. This rather unique design results in a frequency response flat to over 200 kc. Sensitivity of the transducer is quite low however; the change in capacitance is approximately 0.005%/psi. The transducer is therefore limited to use at high pressures.

A general discussion of miniature pressure cells is presented in reference 11. This reference also includes in its discussion several of the pressure transducers previously mentioned in reference 14. Of particular interest, however, is a discussion dealing with fabrication techniques of small diaphragm type variable capacitance transducers. A technique for reducing diaphragm thickness to the desired value by etching in acid is described. The two chief advantages of this technique are the ability to obtain close tolerance in diaphragm thickness and the reduction of internal stresses in the diaphragm as compared with stresses obtained in a machining process. The diaphragms were etched from an original thickness of 0.008" after machining to a final thickness of approximately 0.003".

Reference 12 describes several types of flush diaphragm variable capacitance pressure transducers, having a relatively high frequency response. These transducers utilize a built-in inductance coil to form a tuned radio frequency circuit. Detailed discussions of the internal and external circuitry are presented.

2.1.3 Piezoelectric Effect Techniques

In recent years considerable effort has been directed toward the development of pressure transducers using barium titanate crystals. References 15 and 16 describe transducers utilizing this material. The transducer described in reference 16 consists of a flush flat metal diaphragm with a barium titanate crystal bonded to the inner surface. Deflection of the diaphragm with pressure sets up strains in the crystal. Due to the piezoelectric effect, a voltage is formed across the two faces of the crystal. A transducer of this type can be constructed relatively small in size with very high frequency response. There are, however, two serious disadvantages. First, temperature effects are very pronounced and second, due to charge leakage effects, the transducer is limited to the measurement of nonsteady pressures greater than 5 cps if a simple measuring circuit is used.

Reference 16 describes techniques by which these two disadvantages can be somewhat minimized. For the transducer described in that reference, temperature effects were reduced by approximately an order of magnitude by the use of concentric crystals. The two concentric sections were polarized with opposite orientation. The charges collected on each section were then of the same sign when pressure was applied to the diaphragm, since the strain in the two sections was of the opposite sign. However, when a change of temperature was introduced, the charge produced in each section was opposite in sign due to the reversed orientation. Even after these measures were taken, however, zero drift as a result of temperature was approximately 0.1 psi/^{o}F for a 0 to 50 psi gage. A detailed description was presented of an electrical circuit which removed the surface charge immediately upon formation and allowed measurement of steady pressures. The chief advantages of this transducer are its large electrical signal without an excitation (using a vacuum tube voltmeter, 200 millivolts of output/psi can be obtained), and its relatively high frequency response (natural frequency for the particular transducer is approximately 15 kc).

Reference 15 describes a barium titanate pressure transducer developed at the Guggenheim Aeronautical Laboratory for the measurement of fluctuating wall pressures in a turbulent boundary layer. This transducer was not a diaphragm type but consisted of a barium titanate disk mounted flush with the tunnel wall and backed by a second barium titanate disk. The two disks were cemented together with silver conductive paint and radio cement in such a manner that the inner silvered surfaces were of like polarity. The reference also describes a cathode follower type circuit used in conjunction with the transducer. Experiments performed on a finished transducer indicated that frequency response was uniform from approximately 5 cps to 50,000 cps. Output voltage was approximately linear with pressure and overall transducer sensitivity was 60.7 millivolts/psi. Temperature characteristics of the transducer were not discussed.

A diaphragm type piezoelectric pressure transducer which utilizes a quartz crystal to obtain the piezoelectric effect is discussed in reference 12. A detailed discussion of transducer design and the design of the electrical circuitry is presented in this reference. The particular transducer discussed has a natural frequency of approximately 40 kc and is capable of measuring pressures from less than 0.1 psi to 20,000 psi.

Reference 12 also describes a rather unusual piezoelectric transducer consisting of a stack of barium titanate crystals surrounded with corprene (to reduce the coupling to the housing) and potted with epoxy resin in the housing cavity. The transducer was developed by the Atlantic Research Corporation and is commercially available under model no. BD-10. This reference also points out the necessity of operating piezoelectric crystals into a very high impedance if flat frequency response in the low frequency range is desired. In order to provide flat frequency response to approximately 2 cps., the reference states that an amplifier of 1,000 megohm input impedance would be necessary.

2.1.4 Variable Inductance Techniques

Reference 17, which deals in general with pressure measuring devices for a blowdown wind tunnel, describes in detail a diaphragm differential pressure transducer using the variable inductance principle. Movement of the centrally located diaphragm in this transducer causes a change in inductance of two sensing coils, one located on each side of the diaphragm. The diaphragm acts as the armature of the transducer. The transducer housing and the diaphragm itself (which is a wavy diaphragm) are all constructed of a nickel-iron alloy (Ni-Fe 420) having good magnetic properties and a low coefficient of thermal expansion. Transducers have been constructed to operate at various ranges of pressure from 0 to 15 mm Hg to 0 to 700 mm Hg by varying diaphragm thickness from 1 mil to 5 mils. Frequency response was determined experimentally and was found to be flat to 300 cycles per second.

The automatic measurement of pressures and associated problems, particularly space limitations, response time, and data recorders, are discussed in reference 18. Advantages and disadvantages of several devices commonly used in pressure measuring systems, namely liquid column, metal diaphragm, Bourdon tube, metal bellows, wire filament, and particle radiation are discussed. Specific examples of transducers employing the above techniques are presented. Of particular note were a diaphragm type transducer employing a Schaevitz linear variable differential transformer to measure diaphragm deflection and a variable inductance type diaphragm transducer. Both of these transducers were relatively large in size, but the principles of operation were of interest.

A reference uncovered in the literature survey which has proved to be of particularly great value is reference 19. In addition to presenting a detailed description of a diaphragm type variable inductance pressure transducer having excellent performance characteristics, this reference also presents criteria for the design of flat diaphragms and the determination of acceleration effects, diaphragm resonance, and acoustical resonance. The transducer itself is relatively small in size being approximately 7/16" in diameter by 1/4" thick. It has been constructed in a number of different pressure ranges from 0 to 0.5 psia to 0 to 100 psia. Overall accuracy including the effects of hysteresis, temperature change, and acceleration is approximately 1% of full scale while linearity is approximately 2% of full scale. Construction details are as follows. The flat initially stressed diaphragm is soldered between two cup-shaped metal case halves, each having a core piece. Diaphragm deflection, resulting from pressure differential, changes the length of the air gap between the diaphragm and core pieces thus changing the impedance of the two coils. A voltage output proportional to the impedance changes is produced by an alternating current Wheatstone bridge circuit in which the two coils are connected in adjacent arms. This type of construction results in an inherently low impendance transducer with minimum stray voltage pickup thus allowing the use of long leads between the gage and its associated readout equipment. A transducer of similar construction but using a single air gap, a single coil, and a flush mounted diaphragm is discussed in section 4.

Design of a variable inductance pressure transducer similar to those discussed in references 17 and 19 is reported in reference 14.

2.1.5 Nulling Techniques

In the design of diaphragm type pressure transducers, the nulling technique is frequently employed. This technique basically consists of counterbalancing the pressure force on the diaphragm with a force on the opposite side of the diaphragm such that no actual deflection is experienced. The two chief advantages of this technique are first, the reduction of strains in the diaphragm and therefore the reduction of hysteresis effects and second, elimination of temperature effects in the diaphragm resulting from dimensional changes and material property changes with temperature.

Reference 20 describes a diaphragm type pressure transducer which operates on a nulling principle. The principle components are a thin (0.001") diaphragm, a system for applying and measuring a reference pressure on one side of this diaphragm, and an electrical contact which senses the null position of the diaphragm. The principle of operation is relatively simple; the reference pressure is gradually increased until the diaphragm makes electrical contact with an insulated electrode, thereby sensing the null position. The known reference pressure is then equal to the unknown pressure acting on the opposite side of the diaphragm. This transducer possesses the advantages of small volume (0.01cc) and high sensitivity. A pressure unbalance of 0.3 to 0.5 mm Hg is detectable up to 200 atmospheres. Its frequency response is, however, quite low. The chief interest of this reference to the authors was the use of the nulling principle in a diaphragm transducer. It has triggered several ideas which substitute for the slowly responding reference pressure some other means of applying force to counteract the effect of the unknown pressure.

A very similar null type pressure transducer is described in reference 14, which makes use of a beryllium-copper diaphragm 0.0005" thick and 1" in diameter. As in the transducer described above, the unknown pressure is counterbalanced by means of a controlled reference pressure. In this transducer design, however, the reference pressure is increased linearly with time until nulling is achieved, as sensed with an electrical contact. A digital output is obtained by the use of a counter which is started as the reference pressure begins to rise and stopped when nulling takes place.

2.1.6 Additional Noteworthy References

In addition to the above references, a number of other references are worthy of mention. These will be presented here along with a very brief statement of their contents.

Reference 21 is a comprehensive work on piezoelectricity. Reference 22 presents relationships for the structural analysis of plates and shells which proved very useful in analysis of diaphragm characteristics. Reference 23 discusses the electrokinetic transducer which measures pressure by means of the streaming potential developed by a polar liquid flowing through a porous plug. References 24 and 25 discuss respectively the theory and an application of the hypsometer. A discussion of pressure measuring instruments for use at high vacuum is included in reference 26. Reference 27 presents a general discussion on laboratory instruments including principles of operation, fabrication techniques, and properties of materials.

During the investigation of the vacuum diode for the application discussed in section 6, reference 28, a comprehensive work on vacuum tubes, proved very useful. References 29 and 30 treat a portion of the work done by the General Electric Research Laboratory on vacuum diodes and triodes. The conduction of electricity in gases is discussed extensively in reference 31.

The investigations performed at this laboratory on the use of the electrical corona discharge for the measurement of air density and velocity are summarized in reference 32. Reference 33 describes the development by this laboratory of a digital pressure gage of the variable capacitance, diaphragm type and includes a fairly extensive bibliography on pressure measurement. Work of this laboratory in the development of the radioactive ionization gage as a flight instrument is reported in references 34 and 35. These reports include references to other work done on this device, e.g., University of Michigan, Electrical Engineering Department and the National Research Corporation. Reference 36 describes a miniaturized Pirani gage for the measurement of pressures from 0.1 to 10 mm Hga with a response time of approximately 1 second.

Determination of the properties of materials was accomplished with the aid of references 37 through 40. Manufacturers' literature was also helpful in this regard.

References 41, 42, 43, and 44 present methods for analyzing and evaluating the frequency response of pressure transducers. Reference 45 discusses a method for extending transducer frequency response by electronic compensation.

2.2 Survey of Industrial State-of-the-Art

In order to draw upon the experience of the commercial instrument firms, written inquiries were made to the major firms of this type in this country. These inquiries outlined briefly the design requirements of the reported program and requested information on pressure transducers presently being produced by each of the firms. In addition, the inquiries requested that, in the event the commercial firms had pressure transducers under development which appeared to satisfy at least some of the requirements, the firms disclose any information which they felt would be of value and which they would be willing to disclose.

The following is a list of the firms to which inquiries were made:

Giannini Controls Corporation
Duarte, California

International Dynamics Corp.
Somerville, Massachusetts

General Electric Company
Schenectady, New York

Technology Instrument Corp.
Acton, Massachusetts

Dynametrics Corp.
Burlington, Massachusetts

Consolidated Electrodynamics Corp.
Pasadena, California

Endevco Corporation
Pasadena, California

Trans-sonics Inc.
Burlington, Massachusetts

Wiancko Engineering Co.
Pasadena, California

Ultradyne Inc.
Albuquerque, New Mexico

Atlantic Research Corp.
Alexandria, Virginia

Kistler Instrument Corp.
North Tonawanda, New York

Colvin Laboratories Inc.
East Orange, New Jersey

Photocon Research Products
Pasadena, California

Bourns Laboratories Inc.
Riverside, California

Statham Instruments Inc.
Los Angeles, California

The Decker Corporation
Bala-Cynwyd, Pennsylvania

Massa Division
Cohu Electronics Inc.
Hingham, Massachusetts

Detroit Controls Division
American Standard Corp.
Detroit, Michigan

Replies were received from all of the above firms and included literature on present production pressure transducers. Most of the firms, however, stated that their present pressure transducers were not suitable for the desired application, particularly in consideration of the small size required. Encouraging replies were received from several firms, however, and personal visits were made to these.

During the study phase of the program, it was learned from reference 46 that a unique pressure measuring device having no moving parts was being developed by the International Dynamics Corporation, Somerville, Massachusetts. During subsequent correspondence and visits to that company, additional information was obtained on their "Baroducer" pressure transducer which led to the letting of a subcontract for the development and fabrication of two temperature compensated Baroducer units. Further details as to design and performance of this transducer are presented in section 4.

In considering the development of the resistance-shunting pressure transducer discussed in detail in section 7, the problem of obtaining a thin resistive film presented itself. Through correspondence and personal visits to the Technology Instrument Corporation, Acton, Massachusetts, a great deal of valuable information on the techniques of vacuum depositing resistive metal films and on the properties of these films was obtained. Further details on this topic are presented in section 7.

Considerable background information on the use of the diode principle as a means for obtaining an electrical output from the deflection of a metal diaphragm was obtained by a personal visit to the General Electric Research Laboratory in Schenectady, New York. During this visit several reports were obtained, references 29 and 30, dealing with the fabrication and properties of small heaterless diodes. Further details on the application of the diode principle for the measurement of pressure are presented in section 6.

Details of the work done by the Giannini Controls Corporation, Duarte, California on the development of a semiconductor pressure transducer of very small size are given in section 5.

3. NEWLY EVOLVED TECHNIQUES AND ADAPTATIONS OF PROVEN TECHNIQUES

Considerable effort was expended in the evolution of new techniques for unsteady pressure measurement, and in the adaptation of proven techniques, to be used in the design of a pressure transducer which would meet the performance specifications summarized in section 1 of this report. It should be borne in mind that although some of the following techniques possess serious disadvantages, by modification or by combination with other techniques, practical transducers may possibly be obtained. In other words, some of the ideas expressed here may effectively provide a trigger for a new and more practical transduction technique. Figures referred to in this section are drawn out of scale to better illustrate operating principles. In all cases, the thickness-to-diameter ratio is greatly exaggerated, and the cross section of the base plate is circular.

The pressure transducers utilizing newly evolved techniques and adaptations of proven techniques include the resistance-shunting pressure transducer, the diode pressure transducer, the variable inductance pressure transducer, variable resistance pressure transducers, the variable capacitance pressure transducer, the magnetic-resistive pressure transducer, the nulling magnetic pressure transducer, the electrostatic pressure transducer, the vapor pressure transducer, the radioactive ionization gage, the hypsometer, the corona discharge gage and the cavity resonator pressure transducer. The resistance-shunting pressure transducer and the diode pressure transducer are treated at length in sections 7 and 6 respectively. Upon completion of Phase 1 of the program, these were judged both by the authors and the sponsoring agency to warrant further development and such development was therefore undertaken under Phase 2 of the program. A brief discussion of the remaining types follows.

3.1 Variable Inductance Pressure Transducer

Figure 1 is a schematic diagram of a diaphragm type variable inductance pressure transducer which was considered for the present application. It is similar in principle and construction to the variable inductance transducer described in detail in reference 19. The transducer of that reference is a differential type device in which a stretched diaphragm separates two air chambers, each of which contains an inductance coil. A pressure difference between the two chambers causes a deflection of the diaphragm changing the lenths of the air gaps between the diaphragm and the two core pieces, and thus changing the impedance of the two coils. The coils are connected in adjacent arms of an AC Wheatstone bridge circuit in order to obtain a voltage output proportional to the impedance changes.

In the presently discussed design, a single diaphragm is utilized which is flush mounted on the surface of the transducer. The space between the flush diaphragm and the base plate is evacuated in order to provide an absolute reference. This type of construction has the advantage of providing the flush diaphragm, with its inherently high frequency response (due to the elimination of the problem of acoustical resonance), and also allows a considerable reduction in the size of the transducer. The chief disadvantages as compared with the transducer of reference 19 are decrease in sensitivity, increase in nonlinearity, and increase in temperature effects. Preliminary calculations illustrate that adequate frequency response and desired insensitivity to acceleration effects can be achieved. Nonlinearity will be of the order of 3% of full scale and the addition of a linearizing circuit in the external readout equipment might be necessary. Temperature effects can be minimized by constructing the diaphragm and the backing plate all of the same material, preferably an alloy having a low coefficient of thermal expansion. This material must also have good magnetic properties, i.e., high initial permeability. A signal generator putting out a 20 kc sinusoidal wave form and perhaps an additional DC bias would be the only power requirements. Either a current or a voltage source could be used, the other quantity of the two being measured and corresponding to pressure. The output of the device would be sufficient to bypass preamplification and the inherently low input impedance would minimize leakage and noise problems.

3.2 Variable Resistance Pressure Transducers

Various types of variable resistance pressure transducers were considered during the study phase including the bonded strain gage type diaphragm pressure transducer. None of the devices of this type showed exceptional promise. The bonded strain gage type, for example, would be quite difficult to fabricate in the desired size. In addition, the change in resistance for maximum pressure would be small. Present day strain gages have gage factors slightly greater than 2, where gage factor is the ratio of dimensionless resistance change, $\delta R/R$, to strain, $\delta L/L$. Since the maximum allowable strain for most diaphragm materials is approximately 1×10^{-3} inches/inch, the maximum resistance change experienced by the bonded strain gage type transducer for full scale pressure measurement would be in the order of several tenths of a percent. It would then be necessary to resolve this small change in resistance to a fraction of a percent in order to obtain the desired accuracy. In the final analysis this would mean resolving changes in resistance of the order to 0.001%.

In addition to the problems of resolving such small resistance changes, one must consider the effect temperature would have on such an instrument. Unless a two active arm or four active arm bridge circuit were employed with that number of strain gages bonded to the diaphragm, the effect of temperature would almost certainly be in excess of the desired specifications. All things considered, the bonded strain gage type transducer was regarded as impractical from the standpoints of fabrication, resolution of the very small resistance changes, and temperature sensitivity.

Various other types of variable resistance pressure transducer techniques were considered. As mentioned in section 2.1 of this report, reference 7 discusses a number of variable resistance transduction techniques. Before this reference was found, techniques employing conducting particles suspended in a soft material such as rubber or plastic were considered. It was thought that by properly orienting such particles the overall resistance might be made a function of pressure. The above reference reports on an experimental investigation of very similar devices and concludes that stability and temperature effects are excessive.

The use of a modification of the standard carbon pile resistor was also considered. The very high temperature sensitivity of such a device however, renders its use impractical for the desired application.

3.3 Variable Capacitance Pressure Transducer

Due to its simple geometry, the variable capacitance diaphragm type pressure transducer, as illustrated in Figure 2, was given serious consideration. The geometry is desirable due both to the small thickness, relative to the diameter, and to the relative ease of fabrication. The chief disadvantage, unfortunately, is a very serious one. With the necessary small area of the capacitor plates, the capacitance and the change in capacitance are both small in magnitude. The change may then be swamped by the effects of stray capacitance in the leads. The previous references dealing with variable capacitance type transducers (references 1, 2, 3, 4, 5, 11, 12 and 14) treat this problem at length and illustrate that great care must be taken in shielding the leads and in the design of the external circuitry to minimize this effect. Due to the small amount of space available in the present application, this poses serious problems.

In addition to the capacitance measuring circuits described in the references, several new circuits were designed and analyzed, but none was found which was capable of reducing the effect of stray capacitance and increasing the resolution to the point desired.

3.4 Magnetic-Resistive Pressure Transducer

When a current carrying conductor is placed in a strong magnetic field with field direction perpendicular to current flow, the deflection of the migrating electrons by the magnetic field causes an effective increase in the resistance of the conductor. This increase in effective resistance is proportional to field strength. An attempt was made to design a pressure transducer based on this phenomenon. The design would consist basically of a current carrying coil located in a magnetic field, where the magnetic field would vary in strength as a result of a change in air gap. The air gap change could be accomplished by the use of a flush diaphragm constructed of magnetic material and a base plate with core piece also constructed of magnetic material.

Limited theoretical information was available for use in predicting the magnitude of the effect of the above phenomenon. Several laboratory experiments were therefore carried out in which current carrying coils were immersed in strong magnetic fields and the voltage drop measured for both the in-field and out-of-field conditions. Results of these experiments indicated that the maximum effective resistance change would be approximately 0.1%. A pressure transducer using this phenomenon would therefore have very limited sensitivity; further work on the device was abandoned.

3.5 Nulling Magnetic Pressure Transducer

A device which at first glance showed tremendous potential, but which was later shown to require extremely large power input, is illustrated in Figure 3. The device is basically a nulling type diaphragm transducer in which the pressure force on the diaphragm is counteracted by an electromagnetic force. As illustrated in the figure, current is passed through a conductor located between opposing poles of two permanent magnets. The action of the magnetic field upon the current carrying conductor results in a force opposite in direction to the pressure force. Since the current carrying conductor is attached to the diaphragm, this force counterbalances the pressure force. The current is applied through electrical contacts which are automatically broken when the magnetically induced force exceeds the pressure force. The average current is then proportional to the unknown pressure acting on the exterior surface of the diaphragm. This device originally showed great promise since the internal impedance is low and the necessary circuitry exceptionally simple, since fabrication appears feasible, and since temperature effects are almost non-existent. In addition, it possesses the usual traits of a diaphragm transducer in regard to high frequency response and relative insensitivity to acceleration. The idea has been all but discarded, however, since subsequent calculations showed that for a diaphragm area of approximately 0.25 cm^2 and for the desired maximum pressure of 2 atmospheres, the current required was several thousand amperes. Power required would then be in the kilowatt range creating almost insurmountable problems in power supply and heat dissipation. The current requirements could be considerably reduced by decreasing the diaphragm area. However, since the required reduction of area is so large, fabrication difficulties would be quite formidable. In addition, acceleration effects would increase for such a design modification. Several variations of the above principle were investigated, but none showed increased potential.

3.6 Electrostatic Pressure Transducer

Another technique of measuring unsteady pressures, as discussed in reference 33, is the electrostatic pressure transducer. A modification of the original device of that reference is illustrated in Figure 4. The device is basically a nulling transducer in which the pressure force on a flat diaphragm is counterbalanced by the electrostatic force induced between the diaphragm and another metal plate by the application of a DC voltage. The electrostatic pressure is increased by increasing the DC voltage until this pressure exceeds the unknown pressure. At that point, electrical contact is broken between the diaphragm and the insulated contact terminal illustrated in Figure 7. The unknown pressure may then be related to either the peak DC voltage or to the time required to reach peak voltage.

Since the electrostatic force is an attractive force, the stationary plate must be positioned above the diaphragm and perforated to allow the unknown pressure to act on the diaphragm. This configuration poses problems in frequency response due to pneumatic lag through the porous top plate. A second serious disadvantage exists. To avoid spark breakdown between the two plates, the maximum voltage applied must be less than approximately 300 volts as determined from relationships between spark breakdown, voltage, pressure and spacing presented in reference 31. Maximum voltage is directly proportional to plate spacing and, for the dimensions required, spacing must be less than 10^{-4} to 10^{-5} inches in order that voltage be less than approximately 200 volts. This extremely small spacing poses fabrication difficulties and difficulties arising from the effect of small dust particles which could conceivably enter through the openings in the top plate and lodge between the plate and the diaphragm. The chief advantage of this transducer is its almost complete insensitivity to temperature changes as a result of the nulling principle on which it is constructed. It is also quite insensitive to the effects of acceleration.

3.7 Vapor Pressure Transducer

In search of another technique for constructing a null type diaphragm pressure transducer, the vapor pressure transducer illustrated in Figure 5 was investigated. The device is basically a sealed capsule, the top surface of which is a flush mounted metal diaphragm. All permanent gases are removed from the capsule and it is partially filled with a fluid, the temperature-vapor pressure relationship of which is known. Power is supplied to an internal electric heater coil which heats the fluid until the vapor pressure equals the unknown air pressure, at which point electrical contact between the metal diaphragm and an insulated dectrode is broken and power to the heater interrupted. The temperature of the fluid is then measured by means of a thermocouple, thermistor, or resistive element and the vapor pressure deduced from this temperature measurement.

It is obvious that, due to the thermal capacity of the fluid and the time lag of the temperature measuring device, the frequency response of this transducer would be greatly deficient. Sample calculations show that, assuming the fluid is 3 centistoke Dow Corning 200 fluid, the vapor pressure-temperature relation for which is known, and for a transducer of the size desired, the amount of energy required to change the temperature of the fluid an amount corresponding to a two atmosphere change in vapor pressure is 0.324 joules. The power necessary, therefore, to make this change in the required time of 10^{-4} seconds is approximately 3 kilowatts. Provided the unknown pressure is decreasing, additional means of removing heat over and above the normal loss by conduction, convection, and radiation to the transducer surroundings would be necessary in order to achieve high frequency response.

The following is a summary of the advantages and disadvantages of this device. It is insensitive to steady state changes in temperature provided that the vapor temperature corresponding to minimum vapor pressure is greater than the maximum ambient temperature of $+100^{\circ}C$. The external circuitry is relatively simple. On the other hand, the frequency response is very low. Temperature gradients, which will almost certainly exist due to the application of power to the heater coil, will cause difficulties in determining the average fluid and vapor temperature. The presence of the fluid in the transducer will increase sensitivity to acceleration and will possibly cause a change in performance with change in the orientation of the transducer.

3.8 Radioactive Ionization Gage

In the past several years, a considerable amount of work has been done at this laboratory in the development, particularly for flight application, of the radioactive ionization gage as reported in references 34 and 35. The operation of the radioactive ionization gage relies on the creation of ions, by bombarding air at the pressure of interest with radioactive particles, and the collection of these ions on a charged collector plate. The resulting ionization current is proportional to air density. It is conceivable that this principle could be applied in the design of a transducer to meet the proposed requirements. Small size, rapid response, and relative freedom from the effect of acceleration forces could be quite readily achieved. For the range of pressure of interest, however, quite large collector voltage is required in order that the ionized particles be collected before recombination occurs. In addition to this, the ionization current is very small in magnitude (approximately 10^{-8} to 10^{-12} amperes) posing very difficult leakage and circuitry problems. Finally, since the radioactive ionization gage is a density measuring device, a simultaneous, rapid response measurement of temperature would be necessary in order to provide adequate information for the calculation of pressure.

3.9 Hypsometer

The hypsometer (references 24 and 25), which relates boiling point of a liquid to ambient pressure, was considered for the present application. The design of a device utilizing this phenomenon requires the control and measurement of fluid temperature. This disadvantage leads, however, to the advantage that the device is insensitive to ambient temperature except for possible temperature gradients established in the device as a result of changes in ambient temperature. Since the output of the device is a temperature which is a function of pressure, the readout would be relatively simple; a thermocouple, thermistor, or temperature-resistance device could be utilized. On the other hand, the device is inherently low in frequency response and for this reason was concluded to be unsuitable for the present application.

3.10 Corona Discharge Gage

In the past, extensive investigations were made at this laboratory of the electrical corona discharge from the tip of a fine wire. This work was performed under the direction of Dr. F. D. Werner, former head of the Instrumentation Research Group, and is reported in reference 32. The phenomenon was originally exploited for the measurement of pressure. Subsequent work indicated that it was in actuality density dependent.

The configuration studied consisted of a fine wire and a circular plate perpendicular to the wire. The current passing between the pointed electrode and the plate was found to be a function of the potential difference between the two electrodes, the spacing between point and plate, and the density of the air present. Only the operation in air was investigated, but theory predicts also a dependence upon gas composition. Performance was found to be dependent upon the respective polarities of the point and plate; for a negative point the device was known as a "negative corona" while for a positive point it was known as a "positive corona" Empirical equations for the relationship between corona current and the above mentioned variables are as follows for the positive corona and the negative corona respectively:

$$I = 1.91\,(\rho/\rho_o)^{-3/2}\, s^{-5/3}\left(\frac{V}{1000} - 0.5\right)^3 \qquad (1)$$

$$I = 37\,(\rho/\rho_o)^{-8/3}\, s^{-7/3}\left(\frac{V}{1000} - 0.5\right)^{8/3} \qquad (2)$$

where I is current in microamperes, V is voltage in volts, s is the spacing between point and plate in mm, ρ is the density of the air, and ρ_o is the density of air at 0^oC and 760 mm Hga.

Several advantages of a corona discharge density gage for the present application are its very high frequency response (approximately 500 kc) and its inherently small size. In addition, as a density measuring device it is relatively temperature insensitive. Assuming the fine wire point could be rigidly supported, which may be a rather poor assumption, the effects of acceleration would be negligible. The device has some serious disadvantages. For the pressure range desired under the subject contract and for the corresponding density range, potential differences as high as 5,000 volts DC would be required for gage operation. The fine wire points, which for best operation should be approximately 10 microns in diameter or less, are extremely fragile and subject to contamination after short periods of use. Finally, since the device is density sensitive as opposed to pressure sensitive, the measurement of ambient temperature with a very high frequency response device would be required.

Use of the corona discharge to measure spacing was also considered. To accomplish this, the inside surface of a diaphragm could be used as the plate of the corona and the fine wire point mounted on the base plate of an evacuated capsule. By this means the problem of point contamination could be somewhat reduced and a measure of protection given to the very delicate point. Since the electrode spacing would then be a function of pressure due to the action of the diaphragm, since density would be constant within the evacuated chamber, and since the device is relatively temperature insensitive, the most serious problems remaining would be those of the necessary high potential, possible change of gas composition within the chamber, and point contamination.

3.11 Cavity Resonator Pressure Transducer

The last device considered utilized the principle of a cavity resonator. In construction the device would be similar to the variable capacitance transducer described earlier. It would, however, be powered by a very high frequency source, source frequency being determined by the natural frequency of the cavity formed between the diaphragm and the base. Variations in pressure would be detected by either noting the change in resonant frequency of the cavity due to diaphragm deflection or by noting the attenuation of imposed oscillations due to the device not operating at its exact resonant frequency.

Because of the small spacing available (approximately 0.010"), the source frequency required would be excessively high, in the order to 10^6 megacycles. The device was, therefore, considered unsuitable for the present application.

3.12 Restrictions on Capacitive and Inductive Transducers

Two restrictions imposed on the transducer in the specifications are that the imput impedance be less than or equal to 500 ohms and that the output voltage be of sufficient magnitude to preclude preamplification. If a full scale output voltage of 1/2 volt is considered to be sufficient we have,

$$\frac{|E|}{|I|} \leq 500\ \Omega \tag{3}$$

and

$$|E_{max}| \geq 0.5 \text{ VOLT} \tag{4}$$

where E is the output voltage and I is the output current. From these we obtain,

$$|E_{max}|\,|I_{max}| \geq 5 \times 10^{-4} \text{ WATTS} \tag{5}$$

These restrictions allow the use of an inductive device driven by either a constant current generator (the output voltage being proportional to the rate of change of inductance) or by a sinusoidally time varying current generator (the output voltage being proportional to inductance). Since the former involves an integrating detection circuit the latter is preferred. Analysis shows that, if the latter scheme is applied to a device having the specified transducer volume, an operating frequency, ω, in excess of 0.1 rad/sec is required. Since ω would have to be greater than the maximum frequency at which the device is expected to operate (63,000 rad/sec), the restrictions imposed by energy considerations are negligible.

An analysis was also conducted on a capacitive device to determine the effect of the above restrictions. A 500 ohm shunting resistor would be necessary in a device whose output depended on the rate of change of capacitance. This would greatly decrease the sensitivity of the device. The limited capacitive energy storage available dictates that a driving frequency in excess of

4,500 rad/sec must be used if the output is to be proportional to the capacitance. It is questionable that a practical device could be constructed to operate on this principle at a convenient frequency.

4. THE "BARODUCER" PRESSURE TRANSDUCER

The "Baroducer" pressure transducer, discussed in reference 46, is described as to principle of operation and performance characteristics by the following quotation from a sales brochure of the International Dynamics Corporation.

DESCRIPTION: The sensing element in a BARODUCER is a polymer. Electrodes are applied to upper and lower surfaces, and voltage is applied across the polymer. When pressure is applied to a surface of the polymer, the current flowing across the polymer increases. This change in current can be recorded. Since this is a homogeneous polymer the maximum or minimum size is essentially limitless. Whereas the applied pressure necessary to give a full range affects the polymer only as a slight molecular deformation the dimensional changes of the transducer during the operation may for most work be considered zero.

SPECIFICATIONS FOR STRESS GAGE

Operating Ranges - Any, e.g., 0-1 Gm, 0-100, 0-5000, 100-110, 2000-2100, etc. Cut in or out at any given force.

Pressure Overload - Dynamic - Less than 1 second, 10,000 times full range.

Temperature Limits - At present, -5°C to +110°C. Thermal insulation may be used for short periods above or below these limits.

Ambient Conditions - The section of the instrument enclosing Baroducer is hermetically sealed against adverse conditions.

Acceleration - Acceleration component negligible.

Frequency Response - Flat response to 1500 cycles.

Electrical Data - 1.5 to 10^7 ohms, at rest.

Input Voltage - Between 0.2 and 200 VDC.

Output Voltage - Controls up to 90% of input voltage. (20,000 ohm per volt).

Output Current - Maximum 10^{-4} amps (at 200 volts).

Zero Reading Current Flow - 10^{-8} amp.

Thermal Zero Shift (uncorrected) - 1% of full scale/$^{\circ}$C.

Repeatability - ±2.5% on full scale deflection.

Hysteresis - Negligible

Output Characteristic Curve - Linear or logarithmic or special complex forms.

Pressure Connection - Dependent on design.

Electrical Connection - Lead out wires to specification (length, covering, etc.).

Minimum Size - Approximately 1 mm dia. × 1/2 mm thickness.

Minimum Weight - Less than 20 milligrams.

Shape - Any.

Flexibility - Special units may be flexed while operating.

Resolution - Infinite.

In addition to the above information, other characteristics of the "Baroducer", in particular the specifications for its use as a pressure transducer as opposed to a stress gage, were obtained in subsequent correspondence and discussions with personnel of the International Dynamics Corporation. The output versus pressure curve was stated to be very nearly linear up to approximately 20% of full scale load. Between approximately 20% and 50% of full scale load, the relationship approximates a logarithmic curve, sensitivity increasing with increasing load. Above the 50% point sensitivity decreases with increasing load and the output becomes nearly constant at high loads. Hysteresis was stated to be negligible up to 50% load. The effects of strains in the surface to which the "Baroducer" is bonded were also stated to be negligible.

The maximum frequency response of 1500 cps mentioned in the above quotation was actually measured experimentally for a "Baroducer" with a seismic mass attached for use as an accelerometer. Personnel of the International Dynamics Corporation believe that, for the size transducer specified under this program, the desired frequency response flat to 10 kc should be obtainable. Preliminary calculations made by the authors show this to be true provided only that the migration of electrons in the polymer does not in itself limit frequency response.

Probably the most serious disadvantage of the "Baroducer" for the desired application is its temperature sensitivity; the change in output with temperature is approximately 1%/°C. Temperature compensation is possible, however, by the use of a second polymer unit which has approximately the same temperature sensitivity but is pressure insensitive. Use of the two units in adjacent legs of a bridge circuit provides the temperature compensation. Up to the time of publication of this report, quantitative information as to the degree of compensation realizable was not available.

After consideration of the above characteristics of the "Baroducer" pressure transducer, the sponsoring agency requested that a subcontract be let to the International Dynamics Corporation for the fabrication of two temperature compensated "Baroducer" pressure transducers. A best-of-effort type subcontract was therefore let to the International Dynamics Corporation for the design and fabrication of two units to the desired size specifications (0.015" thick by 1/4" by 1/2"). Fabrication of the two units was completed and they were delivered to the sponsoring agency for evaluation.

5. THE GIANNINI SEMICONDUCTOR PRESSURE TRANSDUCER

During the study phase of the program, the authors were informed by the sponsoring agency that the Giannini Controls Corporation, Duarte, California was engaged in the development of a miniature semiconductor pressure transducer. Subsequent correspondence between that company, the authors and the sponsoring agency led to the placement of a subcontract with that company for test data on their semiconductor pressure transducer. A summary of the information contained in the resulting Giannini test report (reference 47) follows. A detailed drawing of the device was not available due to the proprietary rights involved.

The Giannini piezoresistive pressure transducer evaluated under the above mentioned subcontract consisted of a sandwich semiconductor unit bonded with epoxy resin to a heavy rim. The rim provided structural support and, by way of appropriate fittings, a means of applying a pressure differential to the semiconductor sandwich. The sandwich consisted of two separate rectangular plates of specially oriented, cut and processed silicon semiconductor material bonded together with epoxy resin. The dimensions of the semiconductor sandwich were 0.400" × 0.200" × 0.015". The heavy ring was quite large and was intended for use in the laboratory model only. It would be replaced by a small "bathtub" rim and chamber for the prototype device.

The following performance characteristics were determined analytically by Giannini personnel for the above configuration.

Rupture Pressure = 306 psi

Sensitivity (for an input voltage of 1.3 volts) = 128 micro-volts/psi

Natural Frequency = 52 kcps

Acceleration Error for 20 g's Normal to Sandwich = 0.042% full scale (where full scale is taken as the theoretical rupture pressure)

Linearity = ± 2.3%

Zero Error and Hysteresis = Negligible

Temperature Coefficient = .6%/°C

The experimentally determined performance characteristics for the above configuration are as follows.

Sensitivity (for an input voltage of 1.3 volts) = 100 micro-volts/psi

Natural Frequency = above limit of test gear (10 kcps)

Linearity = ±2.5%

Zero Error and Hysteresis = Undetectable

Temperature Coefficient = 2%/°C

The sensitivity, as noted, is based on an input voltage of 1.3 volts. This was the practical upper limit for input voltage based on self-heating considerations. The input impedance of the transducer in the unstressed state was 2,400 ohms.

An examination of the performance characteristics shows that the experimentally determined temperature coefficient is considerably larger than that predicted by theory. This temperature coefficient is in the form of a sensitivity (slope) change, as opposed to a zero shift, and sensitivity decreases with increasing temperature. The Giannini personnel feel that the high experimental value is in part due to thermal creep of the epoxy resin adhesive. They feel that, by the use of a more appropriate adhesive and by an extension of their intrinsic temperature compensation, the temperature coefficient can ultimately be reduced to 0.5%/°C.

The above experimental performance characteristics were measured two days after the sandwich had been cemented to the heavy rim. The results of the pressure and temperature calibrations are illustrated in Figure 6a, which was reproduced from reference 47. Although the subcontract originally called for the calibration to be carried out at -55°C, 25°C, and 100°C, they were actually carried out at 25°C, 36°C, and 42°C due to temperature limitations of the epoxy resin. The pressure calibrations were obtained by exposing one face of the sandwich to atmospheric pressure and the other to a vacuum system. The pressure on the vacuum side was then varied to obtain the points illustrated in Figure 6a. The ordinate of that figure represents the absolute pressure in the vacuum system. The actual pressure differential which the sandwich experienced was atmospheric pressure minus the value on the ordinate; the barometer was not recorded in reference 47.

After an additional two weeks of room temperature aging of the adhesive, another calibration of the unit was made at 25°C. The results are illustrated in Figure 6b. As a result of the aging process, the sensitivity increased to 202 micro-volts/psi for a 1.3 volt input. The unit was tested to destruction; the rupture pressure was 95 psi. The fact that the rupture pressure was considerably lower than the predicted value (306 psi) is attributed by Giannini personnel to the combined effects of structural imperfections in the semiconductor material and inadequate strength of the bonding agent.

Further developmental work is presently being carried out by the Giannini Controls Corporation. A new type of sandwich is being used which consists of a single slice of semiconductor material which has its surfaces diffused with an impurity to change their type. This results in two very thin slices of one type of material separated by a thicker slice of the same basic material. Sandwiches of this type have been fabricated 0.005" thick, and it is expected that an overall transducer thickness of 0.015" to 0.020" is obtainable.

Preliminary calibrations of a sandwich of the latter type yielded the following results, as noted in reference 47.

Sandwich Size = 0.400" × 0.200" × 0.005"

Rupture Pressure = about 50 psi

Pressure Sensitivity = 1.02 millivolts/psi (for 1.3 volt input)

Temperature Coefficient = about 1.5%

6. THE DIODE PRESSURE TRANSDUCER

As noted in section 3 of this report, the diode pressure transducer was one of the two transducer types chosen by the sponsoring agency at the completion of the study phase of the program for further development under Phase 2 of the program. Figure 7 is a schematic diagram of this device as it was originally visualized. The important design features illustrated by this figure include the spherical segment diaphragm (the reason for the choice of the spherical segment diaphragm over a flat diaphragm is detailed in section 7.1 of this report) which forms the anode of the diode, the evacuated space between the diaphragm and the base plate, the oxide coated cathode mounted on the heavy base plate, and the indirect cathode heater.

The operation of the diode pressure transducer is as follows. Movement of the diaphragm as a result of pressure change causes a difference in the spacing between anode and cathode which in turn results in a change in plate current, assuming plate voltage is held constant. Plate current is then a function of pressure. To reduce the effects of change in cathode temperature, the device may be operated in the space charged limited region, i.e., plate voltage is held to a value much below that required to achieve saturation current for the given cathode temperature. For the space charge limited condition, current density, J, can be expressed by the following equation from reference 28.

$$J = 2.335 \times 10^{-6} \left(\frac{V^{3/2}}{D^2}\right); \quad \frac{\text{amps}}{\text{unit area}} \tag{6}$$

where D is the cathode-anode spacing and V is the anode potential in volts. Since D is a function of ambient pressure, it can readily be seen that plate current is a function of ambient pressure. The diode pressure transducer has several attractive features which account for its use by several previous investigators as noted in references 2 and 48. The frequency response of the device depends on the diaphragm characteristics since the time constant of the diode operation itself is sufficiently small to have no significant effect upon the overall frequency response. As will be shown in section 7.1, for a diaphragm type transducer of the approximate size desired, frequency response as high as 10 kc should present no serious problem. The dynamic or static resistance of the diode can be made 500 ohms or less, a maximum output voltage of 1/2 volt or greater can be quite readily obtained, and no elaborate detection circuit is required.

One serious disadvantage of the diode pressure transducer is its nonlinearity. Some intrinsic compensation for this nonlinearity can be obtained by using very small spacing between cathode and anode, of the order of 0.001". Reference 30 indicates that as spacing approaches this value, current becomes inversely proportional to the first power of spacing.

Since the diode, operating space charge limited, still exhibits some temperature dependence, it might be necessary to not only provide a source of heat for the cathode but regulate its temperature as well. Fortunately, temperature regulation would not need to be very precise.

The most serious disadvantage of the diode pressure transducer was disclosed during the design study of Phase 2 of the program. Preliminary heat transfer calculations were made on the diode pressure transducer in order to determine the necessary power input to the diode heater and the expected temperature at the surface to which the transducer would be bonded. Precise calculations were difficult since the results depend upon the material properties of the surface to which the transducer will be bonded and on the thickness of the surface. Approximate calculations indicated that for a heater bonded directly to a metal transducer base plate with only a thin sheet of electrical and thermal insulation separating heater and base plate, heater power required would be prohibitively high, in the order of 100 watts/transducer. However, if the heater is bonded to a thin disk which is separated over most of its area from the base plate by a thin (1 mil) vacuum gap, the required heater power can be reduced, by the attendant reduction in heat conduction, to approximately 1 watt. Unfortunately, the problem of providing a vacuum gap between the indirect cathode heater and the base plate considerably complicates fabrication. In addition, care must be taken to provide adequate support to insure that the indirect heater and cathode are rigid and not subject to significant movement as a result of acceleration forces. Movement of the cathode would, of course, cause extraneous output readings.

In consideration of the above, the decision was made during the performance of Phase 2 of the program to concentrate efforts on the resistance-shunting pressure transducer. Since many of the fabrication techniques evolved for the resistance-shunting transducer would be applicable to the diode transducer, it was felt that success of development of the former device would greatly expedite further development of the diode device. Unfortunately, adequate time and funds did not remain to allow completion of development of the diode pressure transducer.

7. THE RESISTANCE-SHUNTING PRESSURE TRANSDUCER

During the study phase of the program, the idea for a rather unique variable resistance diaphragm type pressure transducer was conceived.

During the past several years, a number of basic techniques have been used to obtain a variation in resistance in a pressure transducer. Some of these techniques have used a strain type element from which a change in resistance with pressure is obtained by one of several techniques of causing a diaphragm, bellows or Bourdon tube to transmit strain to the element. In other techniques, chambers or "pots" of conducting or semiconducting granules have been subjected to stress from a diaphragm with a result that the collective resistance of the pot varies with the pressure. The standard carbon microphone is the prime example of this technique. For still other variable resistance transducers, the variation in resistance is obtained by means of a potentiometer and wiper accuated by a diaphragm or bellows.

The resistance-shunting pressure transducer conceived during this program is even a more basic scheme than those mentioned above. The device consists of a base plate of an electrically insulating material (or of a metallic material coated with an insulating material), a thin stable resistive film bonded to the surface of the base plate, and a flush mounted metal diaphragm of the flat or spherical segment type. Figure 8 illustrates a possible design configuration of the resistance-shunting pressure transducer suitable for fabrication in a very miniature size. As illustrated in this figure, the design, by use of small spacing and a thin diaphragm, allows the diaphragm to strike the resistive element, thereby providing a low resistance shunt across a portion of the element. An increase in pressure increases contact area, decreasing the effective resistance of the thin foil element. Element resistance is then proportional to pressure and may be measured by a relatively simple circuit.

A number of the following sections of this report are quite general in nature and are applicable for most types of diaphragm pressure transducers as noted.

7.1 Frequency Response and Sensitivity Considerations

The specifications of the program required that the output of the transducer be flat within 1% to 10 kc and that the maximum phase shift over that range be less than 5°. The response characteristics of mechanical diaphragms were investigated in order to determine the size, shape and material requirements on the diaphragm to meet the above specifications.

The basic differential equation describing the response characteristics of a diaphragm is

$$f(t) = m \frac{d^2x}{dt^2} + r \frac{dx}{dt} + k x \qquad (7)$$

where f(t) is the pressure force acting on the diaphragm, m is the effective mass of the diaphragm, r is the effective damping coefficient of the diaphragm, k is the effective spring constant, x is the diaphragm deflection, and t is time. If f(t) is a cosine function,

$$f(t) = F \cos \omega t \tag{8}$$

where F is the amplitude of the pressure force and ω is its frequency. The details of the solution of the above differential equation are treated at length in references 6 and 49 and will not therefore be included here. The results are as follows:

$$x(t) = X \cos(\omega t - \phi) \tag{9}$$

where X is given by

$$X = \frac{\frac{F}{k}}{\sqrt{(1 - \frac{m}{k}\omega^2)^2 + \frac{r^2\omega^2}{k^2}}} \tag{10}$$

and the phase lag ϕ is given by

$$\phi = \tan^{-1} \frac{r\omega}{(k - m\omega^2)} \tag{11}$$

These equations can be put in more common form by defining the damping ratio (S) and the undamped natural frequency (ω_n)

$$S = \frac{r}{2\sqrt{km}} \tag{12}$$

$$\omega_n = \sqrt{\frac{k}{m}} \tag{13}$$

Representing F/k by $\overline{X}$, where $\overline{X}$ represents the value of X at $\omega = 0$, equations (10) and (11) can then be expressed as follows:

$$X = \frac{\overline{X}}{\sqrt{\left[1 - (\frac{\omega}{\omega_n})^2\right]^2 + 4S^2(\frac{\omega}{\omega_n})^2}} \tag{14}$$

$$\phi = \tan^{-1} \frac{2S(\frac{\omega}{\omega_n})}{1-(\frac{\omega}{\omega_n})^2} \qquad (15)$$

Figure 9 is a plot of equation (14) illustrating the amplitude ratio $\frac{X}{\overline{X}}$ as a function of $\frac{\omega}{\omega_n}$ with damping ratio as a parameter. Figure 10 illustrates phase lag as a function of $\frac{\omega}{\omega_n}$ with damping ratio as a parameter. A careful study of these two figures illustrates that in order to obtain flat frequency response to relatively high values of $\frac{\omega}{\omega_n}$, considerable damping must be present. On the other hand, if the damping is too high, the phase lag will be excessive. Assuming that frequency response must be flat to 1% we can say that

$$X \leq 1.01\, \overline{X} \qquad (16)$$

The maximum allowable phase shift is 5°.

$$\phi \leq 5° \qquad (17)$$

Substituting equations (16) and (17) in equations (14) and (15) and defining a frequency ratio β,

$$\beta = \frac{\omega}{\omega_n} \qquad (18)$$

one obtains

$$1.01\sqrt{(1-\beta^2)^2 + 4S^2\beta^2} \geq 1 \qquad (19)$$

$$\frac{2S\beta}{1-\beta^2} \geq 0.08749 \qquad (20)$$

Figure 11 is a plot of equations (19) and (20). The cross hatched area under the two curves illustrates the region in which one must operate to satisfy the conditions that error due to frequency response is less than 1%

and phase shift is less than 5^o. This figure illustrates also that, for zero damping, the maximum allowable β is approximately 0.1. By providing sufficient damping to make the damping ratio equal to 0.367, β can be raised to 0.117. However, the damping ratio for flat or spherical diaphragms generally varies from approximately 0 to 0.05. Consideration of the above illustrates that only a very small increase in β can be obtained by increasing the damping ratio of the diaphragm. Hence it is regarded as unwise, in view of the practical problems involved, to attempt to increase the damping ratio of the diaphragm.

It was concluded that, in order to obtain the desired frequency response to 10 kc with a diaphragm type transducer, a diaphragm having an undamped natural frequency of at least 100 kc would be necessary, unless the effective frequency response could be extended by means of an electrical filter network.

Due to the difficulty of obtaining a flat diaphragm with a sufficiently high natural frequency to provide undistorted output over the desired frequency range without inordinate sacrifices in sensitivity, the possibility of using compensating passive electrical filters was considered. Active filters were not considered due to the desirability of minimizing external circuitry and due to the success of investigations, which will be discussed shortly, towards the possible utilization of a spherical segment diaphragm. The characteristics of many filters were investigated both with and without additional shunting filters across the transducer. In spite of the fact that several texts, e.g., references 50 and 51, and persons familiar with filter design were consulted, no satisfactory filter was found. It seems highly unlikely that a passive filter or combination of filters exhibiting the desired characteristics can be obtained.

Looking again at figures 9 and 10, one can see that the use of a diaphragm with a natural frequency only twice the desired maximum frequency of operation ($\beta = 0.5$) would only meet the condition of error in amplitude ratio less than 1% if the damping were relatively high (damping ratio equal to approximately 0.65). When $\beta = 0.5$ and the damping is zero, amplitude ratio is approximately 1.35, which corresponds to an error of 35%. If the diaphragm is damped such that the damping ratio is equal to approximately 0.65, the error in amplitude is less than 1% for $\beta = 0.5$. For this case, however, the phase lag would be approximately 35^o, i.e., greatly in excess of the desired 5^o maximum phase lag. The conclusion was therefore reached that, in order to obtain flat frequency response to 10 kc with the diaphragm type transducer, the diaphragm natural frequency must be approximately 100 kc or active compensation networks must be used.

References 6 and 16 present approximate formulas relating natural frequency, sensitivity, maximum pressure, diaphragm dimensions, and diaphragm material properties for flat diaphragms and spherical segment diaphragms. The following equations describing the performance of flat diaphragm are valid provided diaphragm deflection does not exceed 1/5 the value of diaphragm thickness.

$$\omega_{nf} \cong 12.2 \sqrt{\frac{E}{\rho}} \frac{t_f}{d_f^2} \tag{21}$$

$$\frac{P_{max}}{\sigma_{max}} \leq \frac{4}{3} \left(\frac{t_f}{d_f}\right)^2 \tag{22}$$

$$S_f \cong \frac{0.011}{E} \frac{d_f^4}{t_f^3} \tag{23}$$

where:

ω_{nf} = undamped natural frequency of flat diaphragm (rad/sec)

S_f = sensitivity of flat diaphragm (in/psi)

P_{max} = maximum pressure (psi)

σ_{max} = maximum allowable stress (psi)

E = modulus of elasticity (psi)

ρ = density of diaphragm material (slugs/in^3)

t_f = thickness of flat diaphragm (in)

d_f = free diameter of flat diaphragm (in)

The following equations describing the performance of a spherical segment diaphragm are valid for $y_s/d_s < 0.1$.

$$\omega_{n_s} \cong 16 \sqrt{\frac{E}{\rho}} \left(\frac{y_s}{d_s^2}\right) \tag{24}$$

$$\frac{P_{max}}{\sigma_{max}} \leq 16\, t_s \left(\frac{y_s}{d_s^2}\right) \tag{25}$$

$$S_s \cong \frac{0.0058}{E\, t_s \left(\frac{y_s}{d_s^2}\right)^2} \tag{26}$$

where:

ω_{n_s}	=	undamped natural frequency of spherical segment diaphragm (rad/sec)
s_s	=	sensitivity of spherical segment diaphragm (in/psi)
y_s	=	depth of spherical segment diaphragm (in)
t_s	=	thickness of spherical segment diaphragm (in)
d_s	=	free diameter of spherical segment diaphragm (in)

The use of a flat diaphragm was originally considered desirable for several reasons. Fabrication of flat diaphragms is relatively simple and, when flush mounted, they offer a minimum of disturbance to the airstream. However, when one accepts the necessity of designing a flat diaphragm with a natural frequency of 100 kc, calculations using equations (21), (22), and (23) illustrate that sensitivity is deficient. The spherical segment diaphragm on the other hand offers a considerable increase in sensitivity for a design having comparable frequency response. Although fabrication is more difficult for the spherical segment diaphragm, it is still feasible. In addition, the radius of curvature is large enough for the present design to lead the authors to believe that disturbance to the airstream will not be a serious problem.

Relative performance characteristics of spherical segment and flat diaphragms having dimensions and characteristics consistent with the desired transducer specifications are as follows. The diaphragm material for both cases is assumed to be Ni-Span C, the pertinent material properties of which are $E = 26.5 \times 10^6$ psi, $\sigma_{max} = 65{,}000$ psi = proportional limit, and $\rho = 7.65 \times 10^{-4}$ slugs/inch^3.

For the spherical segment diaphragm, depth (y_s) was assumed equal to 0.004". Desired natural frequency was assumed equal to 100 kc (ω_{n_s} = 6.28×10^5 rad/sec). From equation (24) the diaphragm free diameter was calculated to be 0.1377". Assuming a maximum pressure of 45 psi, diaphragm thickness was found to be 2.05×10^{-4} inch from equation (25).

Substituting the appropriate values from above into equation (26) sensitivity was found to be 2.40×10^{-5} in/psi. Assuming constant sensitivity ($\delta y \ll y$), maximum center deflection of the diaphragm for a 30 psi pressure change was found to be 0.72 mils.

To provide a measure of comparison between the above spherical segment diaphragm and a flat diaphragm, similar calculations were made for a flat diaphragm assuming a free diameter of 0.1377". From equation (21) diaphragm thickness was found to be 5.24×10^{-3} inch. The ratio of thickness to free diameter was found to be consistent with equation (22), i.e., the diaphragm was not being overstressed. Sensitivity was then calculated using equation (23) and found to be 1.039×10^{-6} in/psi.

A comparison of the sensitivities as calculated above shows that $\frac{s_s}{s_f}$ = 23.1. Further calculations indicated that, by the use of a spherical segment diaphragm, adequate overall sensitivity could be obtained for both the resistance-shunting pressure transducer and the diode pressure transducer to preclude preamplification.

7.2 Acceleration Effects

The design requirements of the program called for a transducer accuracy of at least ±1% of full scale including among other effects the effect of acceleration. Arbitrarily defining the maximum error due to acceleration effects as 0.2% of full scale, the force per unit area normal to the plane of the diaphragm caused by acceleration must be less then 0.002 P_{max}, where P_{max} is the maximum pressure the transducer is to accurately detect. The unit force on the diaphragm due to normal acceleration is $t\rho a$ where t is the thickness of the diaphragm, ρ is the mass density of the diaphragm and a is the acceleration normal to the plane of the diaphragm. Diaphragm thickness is then given by the following equation:

$$t \leq \frac{.002\, P_{max}}{\rho a} \tag{27}$$

If P_{max} = 30 psi, ρ = 13 slugs/ft^3, and a = 30 g's = 960 ft/sec^2, t must be less than 0.006" in order that the error due to normal acceleration be less than 0.2 of a percent. This condition is more than adequately met in the present design as will be noted in the following sections.

7.3 Design and Fabrication of a Miniature Resistance-Shunting Pressure Transducer

Efforts toward final design, development, and fabrication of the resistance-shunting pressure transducer during Phase 2 of the program were directed primarily toward obtaining a device of the desired small size. During the study phase of the program a scaled up pressure transducer using the resistance-shunting technique was fabricated in order to evaluate contact resistance problems. This model, illustrated in Figures 12 and 13, was rectangular in shape and quite different in design from the miniature pressure transducer designed under Phase 2 of the program. Its use did, however, indicate that contact resistance problems were not serious. In order to expedite completion of the miniature pressure transducer, efforts were not at first made to fabricate a scaled up model identical in design. When fabrication difficulties prevented completion of the device before the end of the program, a scaled up model transducer was designed and fabricated. The results of this work are detailed in sections 7.4 and 7.7.

7.3.1 Base Plate Design and Fabrication

The curvature of the portion of the base plate which carries the resistive film must be tangent to the diaphragm at the initial free diameter of the diaphragm. As a first approach, a conical base plate surface was used in order to simplify fabrication and to allow a more straightforward calculation of possible future base plate shapes of more complex curvature to provide a more linear transducer output. As illustrated in Figure 8, the angle of the concave-inward conical surface is 6.64° in order for that surface to be tangent to the spherical segment diaphragm at the diaphragm free diameter of 0.138". An overall base plate diameter of 0.180" was chosen in order to allow 20 mils of bonding surface on the radius.

As was noted earlier in this report, consideration was given both to fabrication of the base plate of a metallic material or of an electrically insulating material. The metallic material offers the advantages of being easier to fabricate by normal machining methods. Metallic materials are in general stronger and much more resistant to impact, vibration, and thermal shock which might cause failure of an insulating material. However, if a metallic base plate is used, an insulating layer must be applied to the upper surface of the base plate in order to prevent shorting of the resistive film to the metallic base plate.

Considerable effort was expended toward design and fabrication of metal base plates. The material chosen was Ni-Span C; this choice was dictated by advantages of this material for use in diaphragm fabrication.

It was considered desirable to fabricate the diaphragm and the base plate of the same material in order to avoid possible differences in the coefficient of thermal expansion. Personnel of the Technology Instrument Corporation, Acton, Massachusetts stated that they could coat the metallic base plate with an insulating layer of silicone monoxide by vacuum deposition. They stated also that a resistive metallic film could be deposited over the silicone monoxide, thus achieving all the aims of the design. A number of Ni-Span C base plates were machined with the view of having the above company perform the deposition of films on a subcontract basis. A metal base plate was never completed however due to technical difficulties experienced by the Technology Instrument Corporation in experimentation with the vacuum deposition technique for depositing the silicone monoxide films. In their experimentation they found that pinholes formed in the film allowing electrical shorting of the resistive element to the base. This problem was later solved through the help of a vacuum specialist consultant, but a shortage of time and funds did not allow completion of base plates by this method.

Serious consideration was then given to fabricating the base plate of an electrically insulating material. A number of different materials were considered. The work of the General Electric Research Laboratories in the development of vacuum diodes and triodes fabricated from metals and ceramics suggested the possible use of forsterite or a ceramic of that family for use as a base plate material. An inquiry was made to the American Lava Corporation, Chattanooga, Tennessee to obtain as much information as possible as to what ceramics would be suitable for this use. The two criteria judged most critical for this choice were low porosity and a coefficient of thermal expansion very closely matching that of Ni-Span C. Although several ceramics were found whose temperature coefficient matched that of the Ni-Span C, including American Lava Corporation's AlSiMag 645 ceramic, all were found to have fairly high porosity in the extremely thin sections in which they would be used. The resulting leakage would spoil the vacuum reference so essential to the operation of the transducer. Samples of the most promising type of ceramic (AlSiMag 645) were tested for porosity in order to verify this conclusion. The samples were cemented by means of Pyroceram cement (this cement will be discussed further in section 7.3.4) to a stainless steel tube which matched the temperature coefficient of the ceramic. The tube was then connected to a vacuum system equipped with a Halogen sensitive leak detector and the ceramic was tested for leakage. The samples tested showed high leakage rates when the thickness was reduced to 20 mils or less. No further consideration was given to the use of ceramics as a base plate material.

A number of other electrical insulating materials were considered for use in base plate fabrication. Ordinary sodalime glass was chosen since it has extremely low porosity, since its temperature coefficient matches that of the Ni-Span C and since it is a good electrical insulator. The chief disadvantage of this material is that it must be machined with diamond or carborundum tools and is susceptible to chipping and breakage during the machining operation. Nevertheless, efforts toward achievement of finished base plates as per Figure 8 were relatively successful. After considerable experimentation, a suitable technique for obtaining a high surface finish was evolved. Concurrently with the efforts of this laboratory to evolve a suitable finishing technique, the services of a local optical specialty firm were retained, since it was felt that their more extensive experience in working with glass might result in a more satisfactory base plate. Unfortunately, their efforts were inferior to those of our own model shop.

Examples of glass base plates in various stages of completion are illustrated, along with other small transducer components, in Figure 14.

7.3.2 Diaphragm Design and Fabrication

Ni-Span C was chosen as the most suitable diaphragm material during Phase 2 of the program after consideration of a number of possible diaphragm materials. The property of Ni-Span C which most influenced the authors in this choice was its unique characteristic of maintaining a constant modulus of elasticity, E, over a rather broad range of temperature. The change of modulus over the temperature range of interest in this program is approximately 0.1% as compared to a minimum of 3% for other possible materials. Any change in E is, of course, reflected as a change in sensitivity as illustrated in equation (26). The properties of Ni-Span C are summarized in reference 52.

As noted earlier, a spherical segment diaphragm was used in the design of Figure 8 in order to provide optimum conditions of frequency response and sensitivity. Cutting of the diaphragms to the desired circular shape and stamping to the proper radius of curvature were accomplished with the small jigs illustrated in Figure 15. When adequate precautions were taken in keeping both the jigs and the material clean, the resulting spherical segment diaphragms were entirely satisfactory.

Original calculations based on the use of Ni-Span C for diaphragm material called for a diaphragm thickness of approximately 1/4 mil. The thinnest stock available from the H. A. Wilson Company, the producers of Ni-Span C, was 1 mil. A number of techniques were employed for reducing the thickness of this 1 mil stock to the 1/4 mil. These included rolling, lapping, etching, and a combination of etching and rolling. None of these techniques were adequately successful. The basic problem was that, although the stock could be reduced in thickness by these techniques, the course grain structure of the material allowed formation of small pinholes between grains. Such a situation was of course intolerable due to the resulting leakage through the diaphragm. Further fabrication work was carried out using 1 mil thick diaphragms with the resulting decrease in sensitivity of a factor of four. It is conceivable that, in any further developmental work on the device, the use of a material for the diaphragms which could be rolled or worked to thinner sections might be wise. The resulting increase in sensitivity at the expense of greater temperature effects, would be worthwhile for some applications.

7.3.3 Resistive Element Design and Fabrication

The use of resistance wire for the resistive element of the resistance-shunting pressure transducer was considered undesirable since it was felt that the wire might, due to its thickness, influence the manner in which the diaphragm would deflect. In addition, wire of suitably high resistance was not commercially available and would be extremely difficult to fabricate. It was decided therefore that a thin metal film would be preferable. Reference 53 discusses in detail the various methods which can be used to deposit thin metal films. Of the available methods, vacuum deposition shows the greatest promise.

In the past, the use of vacuum evaporated metal films as resistors has been complicated by the fact that such resistive films are quite unstable, showing changes in resistance with both time and temperature history. In the past few years several investigators, including the Technology Instrument Corporation, have conducted research into the causes of the above problem and have developed techniques by which this problem has been all but eliminated. Personnel of TIC have found that by the proper choice of metallic materials for the film itself, by the use of an appropriate deposition technique (including temperature regulation) and by proper preparation of the substrate, very stable metal films can be obtained. They are presently using Nichrome V with some additional chromium for the metal film. For substrate they have had the greatest success with fused quartz, but have also used pyrex, glass and some other insulating materials. They have found substrate roughness, temperature of the substrate during the evaporation process, and subsequent temperature curing to be very critical as per their effects on the stability of resistance. In order to provide a hard surface for the resistive element and thereby reduce wear, they have recently developed a technique by which they evaporate titanium over the Nichrome film and oxidize this titanium by a curing process. Negotiations had been made, as discussed in section 7.3.1, to have the base plates which were fabricated at these laboratories coated with a metal film by the Technology Instrument Corporation on a subcontract basis. Due to problems noted in that section, sufficient time was not available to have this work done.

It was decided that, to expedite development of the breadboard model, the resistive film would be obtained by the use of No. 05 liquid bright platinum paint produced by the Hanovia Chemical and Mfg. Company, East Newark, New Jersey. This material in the uncured condition is a solution of organic platinum and gold compounds of resinous character in volatile oils and other solvents. When painted on a smooth glass, quartz or ceramic surface and cured at approximately 600°C in an oxidizing atmosphere, it yields a high finish metal film, the metal being predominantly platinum. The approximate DC resistance of this paint when applied full strength is 16 ohms/square. By thinning with acetone and applying with a small sprayer, a resistance of approximately 50 ohms/square was obtained.

Shape of the resistive film used in the miniature resistance-shunting pressure transducer is illustrated in Figures 8 and 14. The width of the film increased linearly with distance from the center of the base plate. This shape was calculated analytically to yield a change in resistance, δR, with change in distance from the center of the transducer, δr, as expressed by the following equation.

$$\frac{\delta R}{\delta r} = \frac{e}{t\,(mr + w_1)} \tag{28}$$

where:

r	=	distance from center of base plate (in)
t	=	film thickness (in)
ρ	=	film resistivity (microhm-in)
w_1	=	film width at center electrode (in)
m	=	$\frac{w-w_1}{r}$
w	=	film width at position r (in)

This shape was chosen with preference over a constant width strip of film since it was expected to provide some measure of compensation for the expected nonlinearity. The accuracy of this intuitive choice was substantiated for a scaled-up transducer, as noted in section 7.7.

7.3.4 Diaphragm Attachment

Provided the transducer design utilizes a metal base plate, several welding techniques show promise for attaching the metal diaphragm to the base plate. These include spot welding, electron beam welding, tungsten-inert gas welding and ultrasonic welding. These welding techniques are discussed in detail in reference 54. During Phase 2 of the program, efforts were made to perfect spot welding techniques. The best results were obtained with a triple prong spot welding jig which made three simultaneous spot welds, thus holding the diaphragm securely in place and preventing distortion from further welding. It was found to be extremely difficult to complete the weld around the periphery of the transducer, since the current flow followed the path of least resistance through the already established spot welds. On the basis of this experimentation, it is considered that electron beam welding or tungsten-inert gas welding would be the best approach for further development work.

For attaching the metal diaphragm to a glass or ceramic base plate, the use of cements and solders was attempted. The soldering technique was suggested by reference 55. In pursuit of the latter technique, pure indium solder and three types of indium alloy solders were obtained from the Indium Corporation of America. While experimentation with these materials illustrated the ability of the solders to bond Ni-Span C to glass, necessity of tinning both surfaces with the solder before joining them made it a rather difficult technique, particularly in the case of the thin Ni-Span C diaphragm. In addition, the strength of the bond was regarded as inadequate. The solders are quite soft even at room temperature and it was felt that hysteresis effects would accompany their use.

After an extensive search of the literature and experimentation with a number of commercial adhesives, Armstrong cement type A-6 was chosen as having the best promise for the desired application. It is an epoxy resin formulation which bonds readily to glass and to the Ni-Span C and can be cured at room temperature provided an adequate amount of accelerator is used. In preliminary experimentation with this cement, a 1 mil Ni-Span C diaphragm cemented to a glass tube (0.180" OD by 0.138" ID) withstood a pressure of 100 psi with no apparent ill effects.

The A-6 cement can be used with one of two accelerators, accelerator A or accelerator E. A high temperature cure, 165°F to 200°F, is recommended for use with the type E accelerator. This was found to be unsatisfactory for the present application since the cement becomes much less viscous when initially raised to high temperature, and tends to flow, apparently due to capillarity, under the diaphragm and over the resistive film. This situation is intolerable since the diaphragm cannot shunt against the film in this case. It was found necessary therefore to use accelerator A and room temperature-cure the cement. Near the end of the program a second cement was discovered which shows promise for diaphragm attachment. It is Eastman adhesive 910, a fast drying adhesive, containing no solvents, which must be applied in a thin coating on the surfaces to be bonded. When the surfaces are forced together with slight pressure the bond sets up almost immediately, within a matter of several seconds. The bonding jig used with the A-6 cement was found to be unsatisfactory; a more elaborate jig would have to be constructed if further work is to be done with the Eastman 910 adhesive.

Another cement which has some appropriately desirable characteristics and which was considered for use in attaching the Ni-Span C diaphragm to the glass base plate is Pyroceram cement No. 95, a product of the Corning Glass Works, Corning, New York. It consists of a finely powdered glass of special composition which is held in suspension by a low viscosity vehicle during application. When it is applied to the surfaces to be bonded, air dried to allow evaporation of the low viscosity vehicle, and then cured at 450°C, a strong leak tight seal is formed. This cement can be used to bond glass-to-glass, metal-to-metal, ceramic-to-ceramic, and combinations of these provided only that the materials have a coefficient of thermal expansion in the range of 8.5 to $11.0 \times 10^{-6}/^{\circ}C$ (soda-lime glass and Ni-Span C are at the lower end of this range).

Experiments performed with the Pyroceram cement (see section 7.3.1) illustrated its ability to provide a strong, leak-free seal. It was not used for bonding diaphragms to base plates because of the problem of preventing oxidation of the Ni-Span C at the 450°C curing temperature.

7.3.5 Final Design of the Miniature Resistance-Shunting Pressure Transducer

As noted earlier, efforts toward obtaining an insulating film on a metal base plate were found to be technically difficult. For this reason and in the interest of expediency, efforts were directed toward the fabrication of a miniature transducer using a soda-lime glass base plate. The following design plan was therefore formulated. A flat circular disk 0.180" in diameter by 0.015" thick was to be ground from soda-lime glass. A conical surface having an angle of 6.64° with the base was to be ground into this disk as per option 1 of Figure 8. A slot approximately 10 mils wide was to be ground from the center of the transducer radially outward to the rim with its bottom surface parallel to the base and level with the center point of the conical surface of the transducer. The resistive film was to be applied by means of the platinum bright paint and cured. The shape of the film was to be as illustrated in Figure 8. A slightly flattened platinum tube was to be laid in the slot with one end near the center of the transducer and the other end extending out beyond the transducer rim. This tube was to be cemented in place by means of Armstrong A-6 adhesive. The resistive film was to be electrically connected to the platinum tube at the center of the transducer by means of indium solder. The base plate was to be placed in the special jig illustrated in Figure 15, and the spherical segment diaphragm was to be positioned on top of it by means of a mandril with a matching spherical tip. Armstrong A-6 adhesive was then to be applied in a 20 mil wide ring around the periphery of the transducer between the base plate and the diaphragm. Finally the transducer was to be evacuated and sealed by means of the platinum tube and a second lead soldered to the edge of the diaphragm.

Difficulties in fabrication prevented the carrying out of the above plan of action and the completion of a miniature resistance-shunting pressure transducer was not achieved. A great deal of difficulty was experienced in machining glass base plates. Considerable care had to be taken to avoid chipping the glass. In addition, extensive experimentation was necessary in order to find a suitable technique for obtaining a high surface polish on the conical portion of the base plate. This was finally achieved, however, difficulty was then experienced in grinding the 10 mil slot. Unless extreme care was taken during this operation the base plates cracked. In addition, during the temperature cycle necessary for curing the platinum bright paint, very slow heating rates had to be employed in order to prevent breakage. To alleviate this problem the conical surface was ground, the slot cut and the other assembly operations carried out while the base plate was still approximately 1/4" thick, with the idea in mind that the base plate could be cut to the desired thickness after assembly had been completed. It was felt that the diaphragm and cement would add sufficient strength to the base plate to allow this to be done. At this stage, time and funds had grown so short that completion was regarded as improbable. Efforts were then directed toward fabrication of the scaled up model discussed in sections 7.4 and 7.7.

It is the strong feeling of the authors that any further development work carried out on the miniature resistance-shunting pressure transducer should be directed toward the use of a metal base plate with the necessary vacuum deposited insulating and resistive films. Machining would be much simpler and breakage would be completely eliminated. The attachment of the diaphragm to the base plate could be accomplished by means of an electron beam welder and a suitable rotary jig. If this should prove unsatisfactory, one could still attach the diaphragm to the base plate by means of a suitable adhesive.

7.4 Design and Fabrication of a Scaled-Up Resistance-Shunting Pressure Transducer

When efforts to complete fabrication of a miniature resistance-shunting pressure transducer failed, the decision was made to build a scaled-up transducer in order to illustrate the basic operating principle and to determine quantitatively the sensitivity and linearity characteristics of the transducer. A scale factor of 5 was used giving a diaphragm free diameter of 0.689" and a value of y, the depth of the spherical segment diaphragm at the center, of 0.02". To expedite fabrication, brass shim stock was used for the diaphragm material. Using equations (24), (25), and (26) and the property values for brass, diaphragm natural frequency was calculated to be 14.8 kc and sensitivity 3.63×10^{-5} in/psi for a 6 mil thick diaphragm.

Details of the design of the scaled up transducer are illustrated schematically in Figure 16; a photograph of the disassembled transducer is included as Figure 17. As these figures show, no effort was made to scale the thickness of the scaled-up transducer. The transducer was made approximately 100 times as thick as the miniature in order to expedite fabrication. The rim to which the diaphragm was attached was machined from 1-1/2" diameter brass rod. Two different techniques were used to attach the diaphragm to the rim. The first employed Eutectic No. 157 soft solder while the second employed Armstrong A-6 adhesive. In both cases the diaphragm was held firmly to the brass rim by means of a mandril having a spherical tip of the same radius of curvature as the diaphragm, 2.97". The base to which the film was attached was machined of fused quartz. The resistive film was applied, by masking the quartz base and spraying with platinum bright paint, and cured at 650°C. A constant width film was used. The quartz base was then cemented to a threaded brass plug by means of which the base could be turned into the diaphragm rim. A 1/8" diameter brass tube cemented to the quartz base provided a means of evacuating the transducer as well as acting as the center electrode. The film was attached to this center terminal by means of indium solder. The whole assembly was rendered leak free by means of the O-ring illustrated in Figure 16.

Details on performance of the scaled transducer are discussed in section 7.7.

7.5 Electrical Circuitry

Since the resistance-shunting pressure transducer has a resistance which is a function of pressure, a large number of potential readout circuits could be used. Figure 18 illustrates an electronic circuit utilizing a 6265 pentode (JAN approved) which can, when used in conjunction with the resistance-shunting pressure transducer, provide a stable voltage output which is proportional to pressure. The maximum output voltage from the circuit is 1.0 volts for an input (transducer) resistance of 250 ohms. Several transducers can be used in series with a maximum error due to the detection circuit not exceeding 0.1%. Figure 18 shows the circuit with two transducers installed.

A power supply voltage of 250 volts is used and the 1000 ohm variable cathode bias resistor, R_k, is adjusted to obtain a plate current of 4 milliamperes. Under these conditions the second grid current is 1.65 milliamperes. The pentode then acts effectively to provide a constant current source to the transducer. The total power dissipated for this configuration is less than 2.4 watts, or less than 1.2 watts per transducer, neglecting losses in the high voltage power supply.

To calibrate the circuit, the plate current is first set at 4 milliamperes. The first transducer is then subjected to zero pressure and R_1 is adjusted such that e_1 is zero. This operation is then duplicated for each additional transducer. If the resistance of the transducer is given by

$$R = R_o - CP \qquad (29)$$

where P is pressure, R_o is resistance of the transducer at zero pressure and C is a constant depending on sensitivity, the corresponding voltage output e is given by

$$e = I_b CP \qquad (30)$$

where I_b is the plate current. The output voltage is therefore directly proportional to pressure.

Where a small number of the transducers are to be used, the 250 volt supply voltage can be provided by a stable mercury battery. If a large number of transducers are to be used, such as for a completely instrumented helicopter rotor blade which might employ as many as 300 transducers, a single power supply could be built to provide the supply voltage for all of the transducers. This power supply could be constructed to operate from power sources available on the aircraft, e.g., nominal 25 volt DC or 400 cycle 115 volt AC. It is conceivable that a pentode could be found which would operate with a supply voltage of 25 volts DC. It is doubtful, however, that the stability of this supply would be adequate to provide the necessary stability of the overall system.

7.6 Evaluation Apparatus

To determine the sensitivity of the miniature transducer to constant accelerations, a small centrifuge was to be used as illustrated in Figure 19. The centrifuge consisted of a circular plate provided with slip rings for bringing out the necessary transducer leads. To simulate the desired normal acceleration of 30 g's, the transducer was to be mounted on the periphery of the plate, 5" from the center, and the plate was to be rotated at 460 rpm in a drill press. To simulate the desired parallel acceleration of 800 g's, the transducer was to be mounted on the surface of the plate, 5" from the center, and the plate was to be rotated at 2377 rpm.

For a precision pressure calibration of the finished transducer, the calibration facility illustrated in Figure 20 was to be used. This facility was, in fact, used for a number of experiments conducted during the program. Calibration of the scaled up resistance-shunting pressure transducer in the range from zero to one atmosphere was carried out in this facility. The instrumentation includes a primary pressure standard produced by the Dynametrics Corporation which operates on the dead weight principle. In the range of pressure of interest, the accuracy of this instrument is approximately 0.03% of reading.

For determination of temperature sensitivity, the finished miniature transducer was to be calibrated in the chamber illustrated in Figure 21. This chamber is provided with Wheaton terminals for bringing out transducer leads and several thermocouples for monitoring chamber temperature. The chamber, complete with transducer, was to be immersed in a fluid bath the temperature which could be varied over the range of interest ($-55^{\circ}C$ to $+100^{\circ}C$).

Evaluation of the response characteristics of the transducers was considered very important since significant deviations from theoretical values could be expected due to difficulty in holding fabrication tolerances. Response characteristics were to be evaluated using the shock tube pictured in Figure 22 and discussed in reference 56. Evaluation of the resulting response data was to be carried out using the methods outlined in references 6, 16, 41, 42, 43, and 44.

The technique to be used consisted of mounting the transducer at the closed end of the expansion chamber of the shock tube. In this position, shock reflection from the closed end would impose a step function change in pressure on the transducer. The output of the transducer during and following the step function change in pressure was to be recorded by means of an oscilloscope or a high speed recorder. The recording equipment was to be triggered by means of a Massa microphone installed just upstream of the end plate. The damped natural frequency (ω_{n_d}) could then be determined directly from this recording. Damping ratio (S) could be determined as noted in the above references by the decay of oscillations. It would then be possible to determine the undamped natural frequency (ω_n) from the following relationship.

$$\omega_n = \frac{\omega_{n_d}}{\sqrt{1 - S^2}} \tag{31}$$

7.7 Experimental Results and Their Analysis

The scaled up resistance-shunting pressure transducer illustrated in Figures 16 and 17 was calibrated in the pressure calibration facility illustrated in Figure 20. The tube leading to the internal volume of the transducer was connected to the calibration facility, and the internal volume was evacuated and stabilized at various pressures between atmosphere and 10 μ Hga. The resulting calibration curve is shown in Figure 23. The resistance of the transducer was monitored with a Leeds and Northrup precision resistance bridge. The data are only illustrated to 700 mm Hga since the transducer was found to be rather unstable at atmospheric pressure (736 mm Hga), as one might expect. This corresponded to a condition of almost zero stress on the diaphragm, and the diaphragm was barely making contact with the resistive film.

If the transducer were used as the design was intended, the internal volume would have been evacuated to a very low pressure and the external pressure would have been varied to obtain the calibration. The calibration would then appear as illustrated in Figure 24, and the unstable condition would have occurred in the region of zero pressure. In the interest of expediency, the former technique was employed. It is completely valid since transducer operation depends only on the pressure differential across the diaphragm.

It is obvious from an examination of Figure 24 that the transducer output is quite nonlinear. Sensitivity varies from 1.5 ohms/psi at zero pressure to 0.13 ohms/psi at 700 mm Hga. On the other hand, the sensitivity is quite high, indicating that, if a method for providing linearity can be evolved, widespread applications for the device would exist. Two techniques have been considered for providing linearity; first, variation of base plate shape and second, variation of the planform shape of the resistive film. The latter was investigated by the authors since it appeared more easily realizable both from the standpoints of analytical determination and fabrication.

The data of Figures 23 and 24 are for a resistive film of constant width. An analysis of these data was made in order to determine the appropriate film planform shape for a linear resistance-pressure relationship. The symbols used in the analysis are defined below.

f = function notation

P = pressure; (mm Hga)

R = resistance of constant width film = $f(P)$; (ohms)

R_o = resistance of constant width film at $P = 0$; (ohms)

r = distance from center of base plate to point of contact of diaphragm with film; (in)

r_o = value of r for $P = 0$; (in)

r_1 = distance from center of base plate to beginning of the constant width film; (in)

e = base of natural system of logarithms

R_t = resistance of tailored film = $f(P)$; (ohms)

R_{t_o} = resistance of tailored film at $P = 0$; (ohms)

s = width of tailored film (measured on circumferential lines) = $f(r)$; (in)

t = film thickness = constant; (in)

ρ = film resistivity; (ohm-in)

C_1 = ρ/t = square resistance of film = constant; (ohms/sq)

The resistance of the constant width film, as illustrated in Figure 24, is given by the following equation.

$$R = R_o - f(P) \tag{32}$$

The function f(P) is illustrated in Figure 25. Two empirical relationships were derived for f(P), a second order equation and an exponential equation. Both fit the experimental data well (the exponential curve is illustrated in Figure 25), but the analysis was simplified by the use of the latter.

$$f(P) = 12.27\,(1 - e^{-.00298P}) \qquad (33)$$

For the constant width film, film resistance can be expressed as a function of r as follows.

$$R = C\,(r - r_1) \qquad (34)$$

Substituting values for R_o, r_o, and r_1, the constant can be evaluated.

$$R = 1.107 \times 10^3\,(r - .0625) \qquad (34a)$$

Since

$$f(P) = R_o - R \qquad (35)$$

one gets from equations (34a) and (35)

$$f(P) = 382 - (1.107 \times 10^3)\,r \qquad (36)$$

From equations (33) and (36), the distance from the base plate center to the point of contact of the diaphragm and the film can be expressed as follows.

$$r = .334 + (1.108 \times 10^{-2})e^{-.00298P} \qquad (37)$$

By differentiation of equation (37),

$$\frac{dr}{dP} = -(.00298)(1.108 \times 10^{-2})e^{-.00298P} \qquad (38)$$

For the desired tailored film, the following differential equation is true.

$$\frac{dR_t}{dr} = \frac{\rho}{t} \frac{1}{s} = \frac{C_1}{s} \tag{39}$$

The requirement for a linear resistance variation for the tailored film dictates that

$$\frac{dR_t}{dP} = C_2 = \text{CONSTANT} \tag{40}$$

But

$$\frac{dR_t}{dP} = \frac{dR_t}{dr} \frac{dr}{dP} = C_2 \tag{41}$$

Substituting from equations (38) and (39)

$$S = -\left(\frac{C_1}{C_2}\right)(.00298)(1.108 \times 10^{-2})e^{-.00298P} \tag{42}$$

By replacing the exponential function in equation (42) by a function of r from equation (37), s can be expressed as a function of r.

$$S = -\left(\frac{C_1}{C_2}\right)(.00298)(r - .334) \tag{43}$$

For a sprayed film of platinum bright paint, C_1 is approximately 50 ohms/square. C_2 was taken to be the sensitivity of the scaled up transducer at zero pressure ($C_2 = -2.62 \times 10^{-2}$ ohms/mm Hga). Substituting these values in equation (43),

$$S = 5.686(r - .334) \tag{43a}$$

Equation (43a) is the equation for a circular sector, proving that the intuitive choice of a circular sector film for the miniature resistance-shunting pressure transducer was amazingly accurate. The conclusion reached through the analysis is that a linear resistance change can be obtained if a film of the shape dictated by equation (43a) is used. Then

$$R_t = R_{t_o} - CP \qquad (44)$$

where C is a constant. Considerable latitude in the film dimensions can be gained by varying the constants C_1 and C_2.

A patent disclosure was made on the resistance-shunting pressure transducer. The ensuing patent search indicated that the device is patentable, and further action is presently being taken by the University of Minnesota with the view of obtaining a patent.

8. GENERAL RESULTS AND CONCLUSIONS

During the literature survey, most existing types of pressure transducers and pressure measuring techniques were investigated. This was done in spite of the fact that many apparently possessed serious limitations, including large size, inherently slow response, undue complexity, insufficient sensitivity, etc. The authors' philosophy was that consideration of an inappropriate device or technique might lead ultimately to a satisfactory device or to a design feature which might be advantageously employed in a satisfactory device. After the investigation of many pressure measuring devices and techniques and in consideration of the design criteria of the program, the conclusion was reached that techniques utilizing the deformation of a structure with pressure load, in particular the deflection of a diaphragm with pressure, exhibited the greatest promise for fulfilling the program aims.

Concurrently with the survey of the literature, a study of the industrial state-of-the-art in pressure measurement was conducted, as noted in section 2.2, to determine if the desired transducer characteristics could be met by a commercial product or development. The results of this study were negative with three exceptions. The International Dynamics Corporation, Somerville, Massachusetts and the Giannini Controls Corporation, Duarte, California both had under development miniature pressure transducers which showed promise for fulfilling the program aims. The Technology Instrument Corporation, Acton, Massachusetts had made significant advances in the development of techniques for vacuum depositing thin resistive and insulating films. This work showed promise for application to the development of several types of variable resistance pressure transducers, in particular the resistance-shunting pressure transducer.

The "Baroducer" pressure transducer developed by the International Dynamics Corporation is discussed in section 4. No firm conclusions have yet been reached on its performance, since the two prototype units developed for these laboratories on a subcontract basis are to be evaluated by the sponsoring agency after publication of this report. It is believed, however, that temperature effects will be greater than desired, since the temperature compensation employed in the prototype is not expected to be perfect, either by the authors or by the personnel of the International Dynamics Corporation. Preliminary information from IDC indicates that the temperature coefficient will be approximately 0.25%/°C.

The Giannini piezoresistive pressure transducer is discussed in section 5. At present, this device is still in the laboratory model stage; a prototype model of the desired size has not yet been completed. Experimental results for the laboratory models indicate that the development work may result in a satisfactory device, provided that two major difficulties can be resolved. First, the measured temperature coefficients of the present models are approximately 2%/°C. Personnel of GCC believe that, by intrinsic temperature compensation, the temperature coefficient can ultimately be reduced to 0.5%/°C. However, even this latter value is considerably greater than the tolerable upper limit for the present application, unless external means of temperature compensation are employed. The second major difficulty with this device is its lack of sufficient sensitivity. For the units evaluated by Giannini and reported in reference 47, the maximum sensitivity was 202 microvolts/psi. To increase the sensitivity, a new type of semiconductor sandwich, having approximately one third the thickness of the previous type, was developed. Preliminary results included in reference 47 show the sensitivity for this latter device to be approximately 1.02 millivolts/psi. Both of the above sensitivity values were determined for maximum allowable input voltage as based on self-heating considerations. It is obvious then that, unless further breakthroughs are made, preamplification would be necessary to increase the output to the desired level.

During the reported program, several original pressure measuring techniques and a number of adaptations of proven techniques were evolved. The diode pressure transducer (section 6) and the resistance-shunting pressure transducer (section 7) received the greatest attention and will be discussed further in subsequent paragraphs. The remaining devices, discussed in section 3, were judged to possess serious limitations for the present application. The most serious and most often encountered limitations were the following; large size, inherently slow response, and temperature sensitivity.

The diode pressure transducer (section 6) was judged, both by the authors and the sponsoring agency, to warrant further development during Phase 2 of the program. A detailed design analysis illustrated that a more complex structural configuration would be necessary to minimize the power requirements of the device. The authors feel that the device still has promise, although fabrication difficulties would be quite formidable.

The resistance-shunting pressure transducer received the greatest attention during the program. The analysis of section 7.7 on a scaled-up transducer indicates that linearity and quite high sensitivity can be achieved with this device, but several other factors should be considered. Equation (37) illustrates that the maximum change in the point of contact between the diaphragm and the film for a one atmosphere change in pressure is approximately 0.010". This is less than 5% of the length of the constant width resistive film. The tailored film defined by equation (43a) covers a very small area, even in the scaled-up transducer. Its width is 0.0625" at the free diameter and decreases linearly to zero only 0.011" toward the base plate center. It is obvious that fabrication of the tailored films would be difficult even for a relatively large transducer. Near perfect alignment of the diaphragm would also be necessary. For these reasons, further development of the resistance-shunting pressure transducer should include efforts toward tailoring the base plate curvature as well as the planform shape of the film. In addition, if technical difficulties involved in obtaining thinner diaphragms are resolved, a factor of four gain in sensitivity can be realized in this area alone.

In conclusion, the resistance-shunting pressure transducer shows good promise for general application in the field of pressure measurement as well as for adaptation to a miniature pressure measuring device. By providing a tailored resistive film and/or base plate, high sensitivity and good linearity characteristics are obtainable. For these reasons, further developmental work appears to be warranted.

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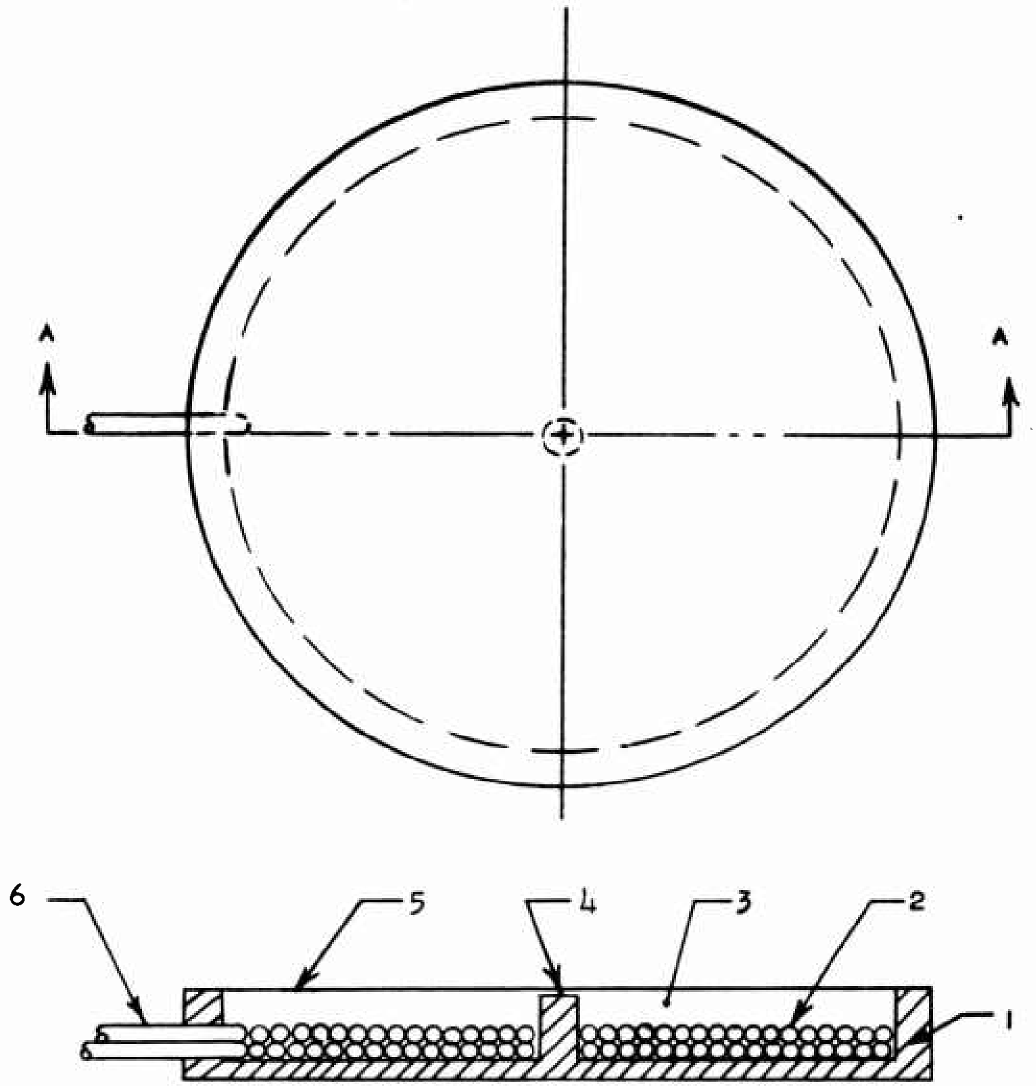
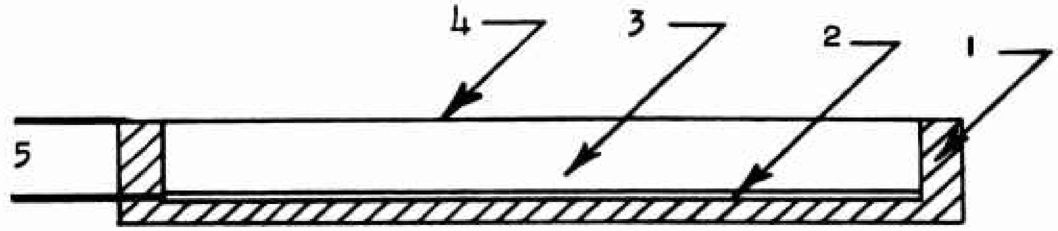


SECTION A-A

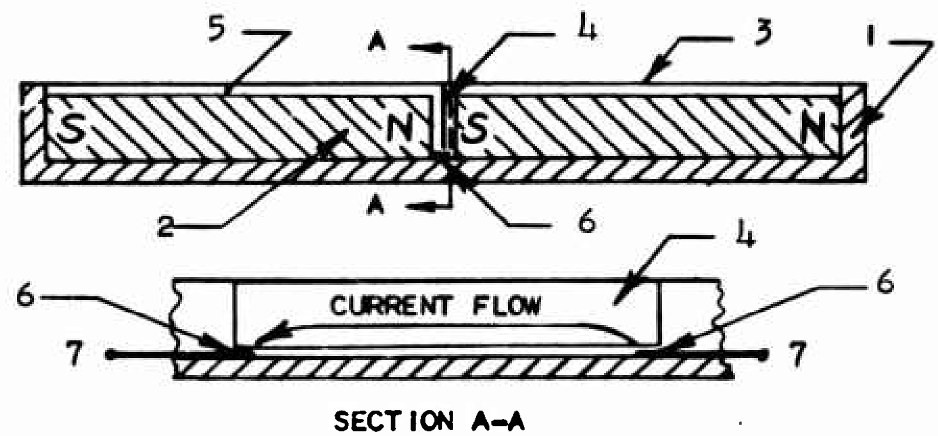
1. Magnetic Material
2. Electrical Windings
3. Evacuated Chamber
4. Variable Air Gap
5. Stretched Circular Diaphragm Made of Magnetic Material
6. To Readout Equipment

FIGURE 1. SCHEMATIC DIAGRAM OF DIAPHRAGM TYPE VARIABLE INDUCTANCE PRESSURE TRANSDUCER



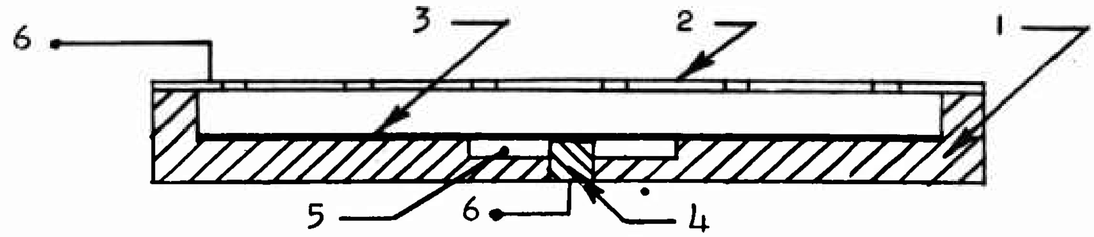
1. Base Plate of Insulating Material
2. Bottom Capacitor Plate
3. Vacuum Dielectric
4. Top Capacitor Plate - Metallic Diaphragm
5. Shielded Leads to Readout Equipment

FIGURE 2. SCHEMATIC DIAGRAM OF DIAPHRAGM TYPE VARIABLE CAPACITANCE PRESSURE TRANSDUCER



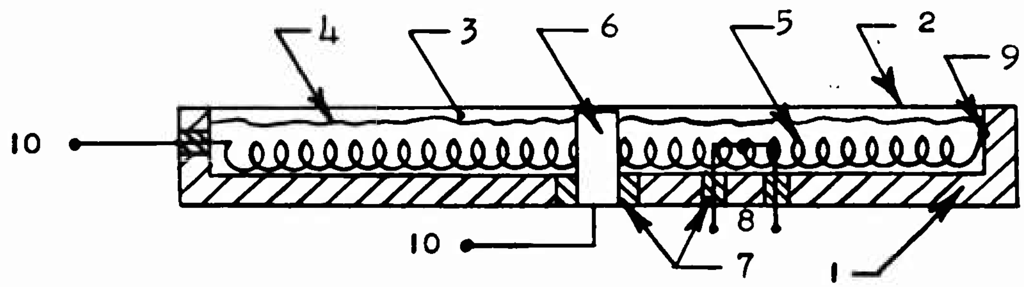
1. Insulating Material
2. Permanent Magnets
3. Thin Diaphragm
4. Conducting Plate
5. Evacuated Chamber
6. Electrical Contacts
7. To DC Power Supply and Readout Equipment

FIGURE 3. SCHEMATIC DIAGRAM OF DIAPHRAGM TYPE NULLING MAGNETIC PRESSURE TRANSDUCER



1. Insulating Material
2. Perforated Metal Plate
3. Thin Metal Diaphragm
4. Insulated Electrical Contact
5. Evacuated Chamber
6. To variable DC Power Supply and Readout Equipment

FIGURE 4. SCHEMATIC DIAGRAM OF DIAPHRAGM TYPE ELECTROSTATIC PRESSURE TRANSDUCER



1. Metal Transducer Case
2. Thin Metal Diaphragm
3. Vapor Chamber
4. Fluid-Vapor Interface
5. Resistance Heater
6. Insulated Electrode
7. Electrical Insulators
8. Temperature Sensing Device (Thermocouple, Thermistor or Resistor)
9. Heater Ground to Case
10. To DC Power Supply and Readout Equipment

FIGURE 5. SCHEMATIC DIAGRAM OF DIAPHRAGM TYPE VAPOR PRESSURE TRANSDUCER

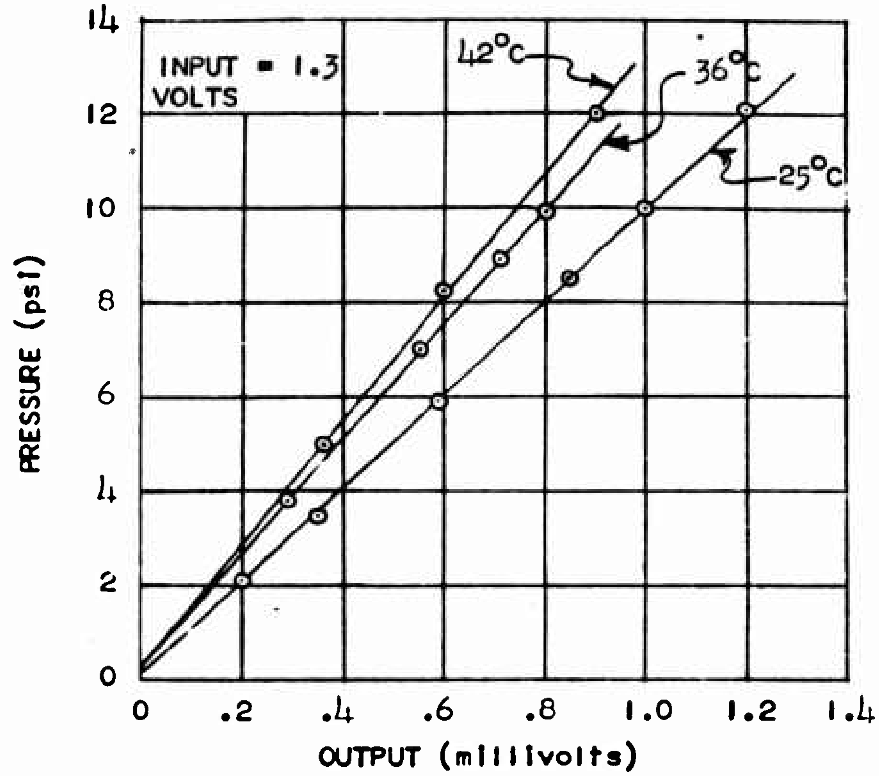


Figure 6a. Adhesive Aged 2 Days

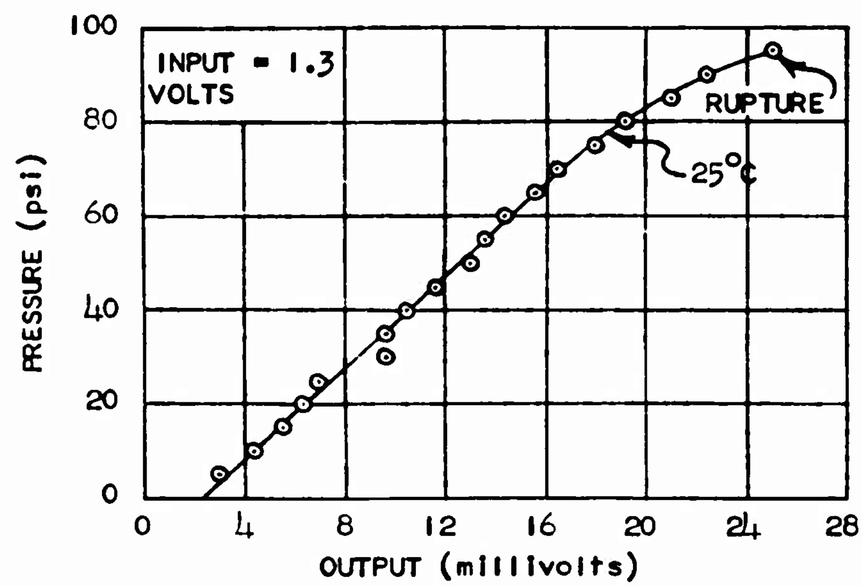
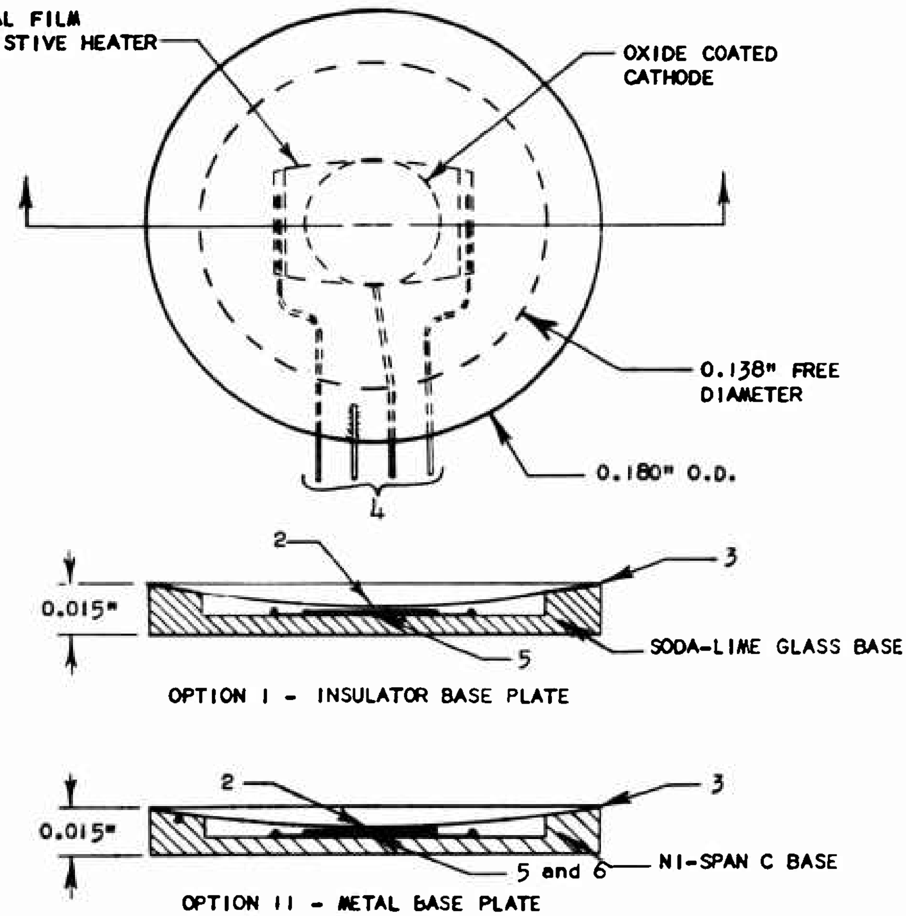


Figure 6b. Adhesive Aged 2 Weeks

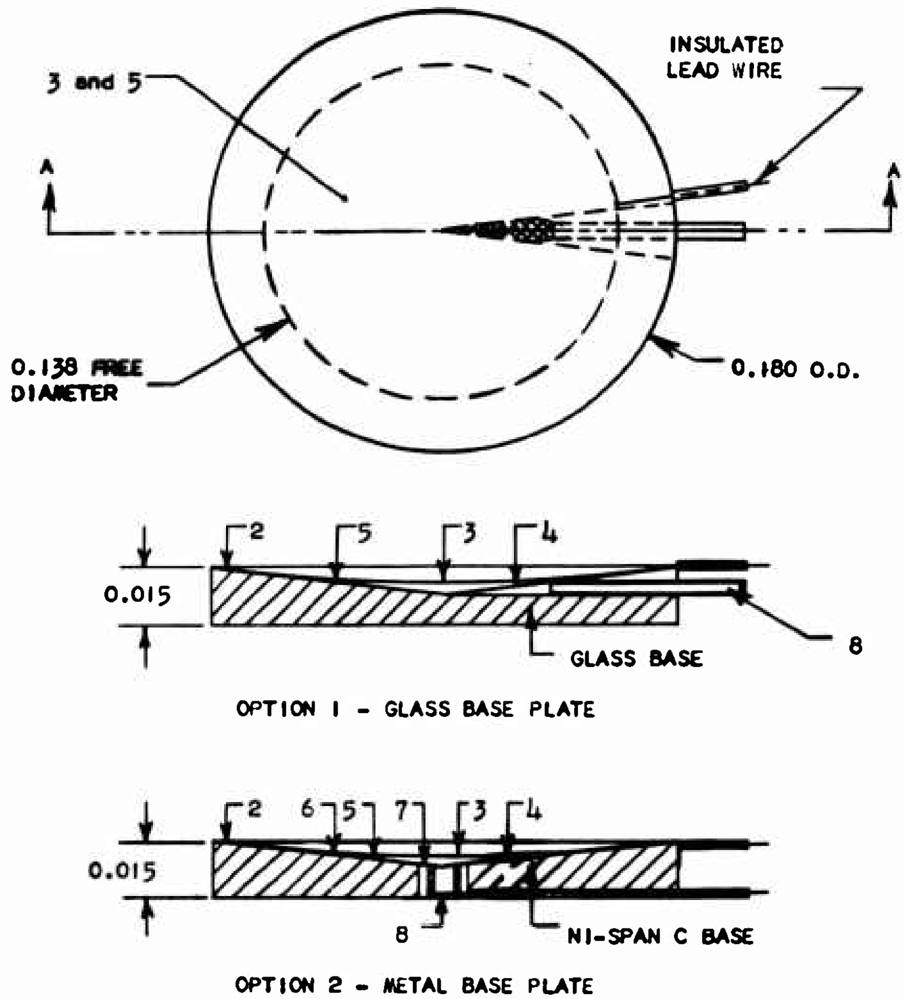
FIGURE 6. CALIBRATIONS OF THE GIANNINI PIEZORESISTIVE PRESSURE TRANSDUCER



NOTES:

1. DRAWING NOT TO SCALE
2. DIAPHRAGM; RADIUS OF CURVATURE IS 0.595". THICKNESS IS 0.25 MIL TO 1 MIL. SPACING ABOVE CATHODE IS 1 MIL FOR ZERO PRESSURE DIFFERENTIAL
3. SOLDER, WELD, OR CEMENT JOINT; FOR CERAMIC BASE, CEMENT JOINT ONLY
4. LEADS - INSULATED WITH PYROCERAM CEMENT FOR METAL BASE
5. CATHODE INSULATED FROM HEATER BY CERAMIC CEMENT OR DEPOSITED FILM
6. HEATER INSULATED FROM BASE BY DEPOSITED FILM

FIGURE 7. DIODE PRESSURE TRANSDUCER



NOTES:

1. DRAWING NOT TO SCALE
2. SOLDER, WELD, OR CEMENT JOINT; FOR GLASS BASE, CEMENT JOINT ONLY
3. DIAPHRAGM; RADIUS OF CURVATURE IS 0.595", THICKNESS IS 1 MIL
4. ANGLE OF CONICAL BASE IS 6.63 DEGREES
5. VACUUM EVAPORATED TAILORED METAL FILM
6. VACUUM EVAPORATED INSULATING FILM BETWEEN BASE AND METAL FILM
7. PYROCERAM CEMENT INSULATOR
8. SEALED-OFF PLATINUM TUBE FOR TRANSDUCER EVACUATION AND ELECTRICAL CONTACT TO METAL FILM BY USE OF INDIUM SOLDER

FIGURE 8. RESISTANCE-SHUNTING PRESSURE TRANSDUCER

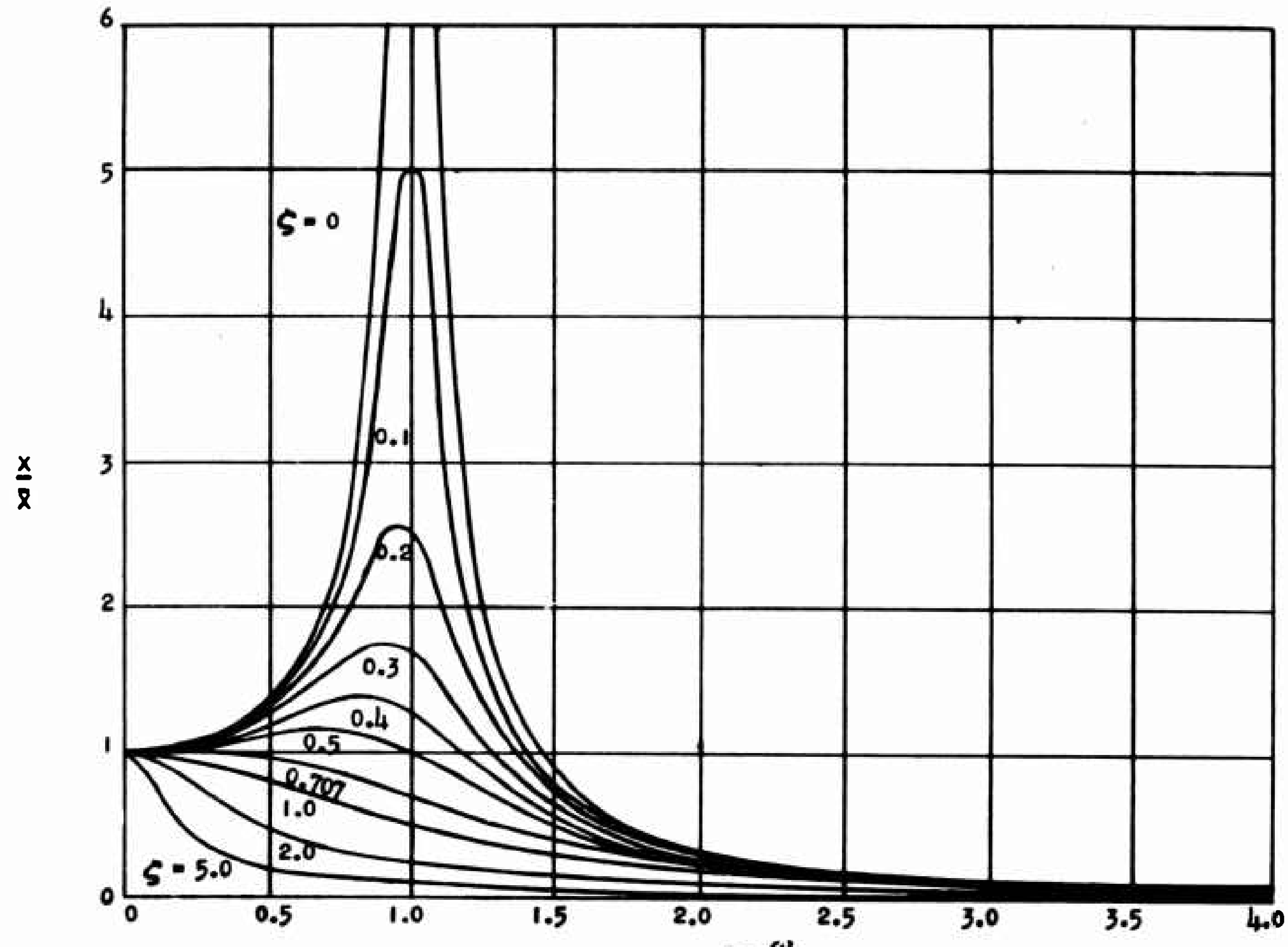


FIGURE 9. AMPLITUDE RATIO VERSUS FREQUENCY RATIO WITH DAMPING RATIO AS A PARAMETER

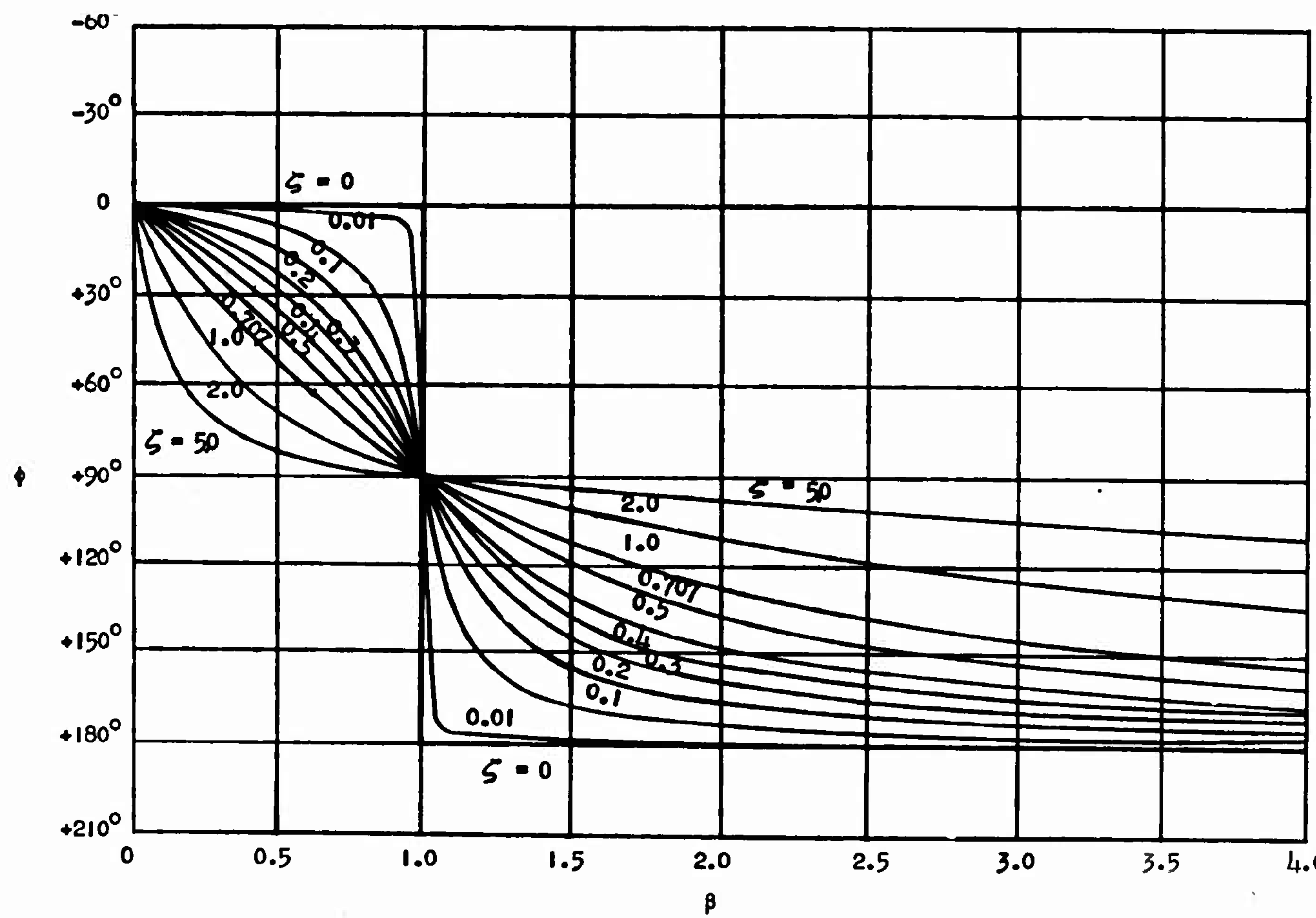


FIGURE 10. PHASE LAG VERSUS FREQUENCY RATIO WITH DAMPING RATIO AS A PARAMETER

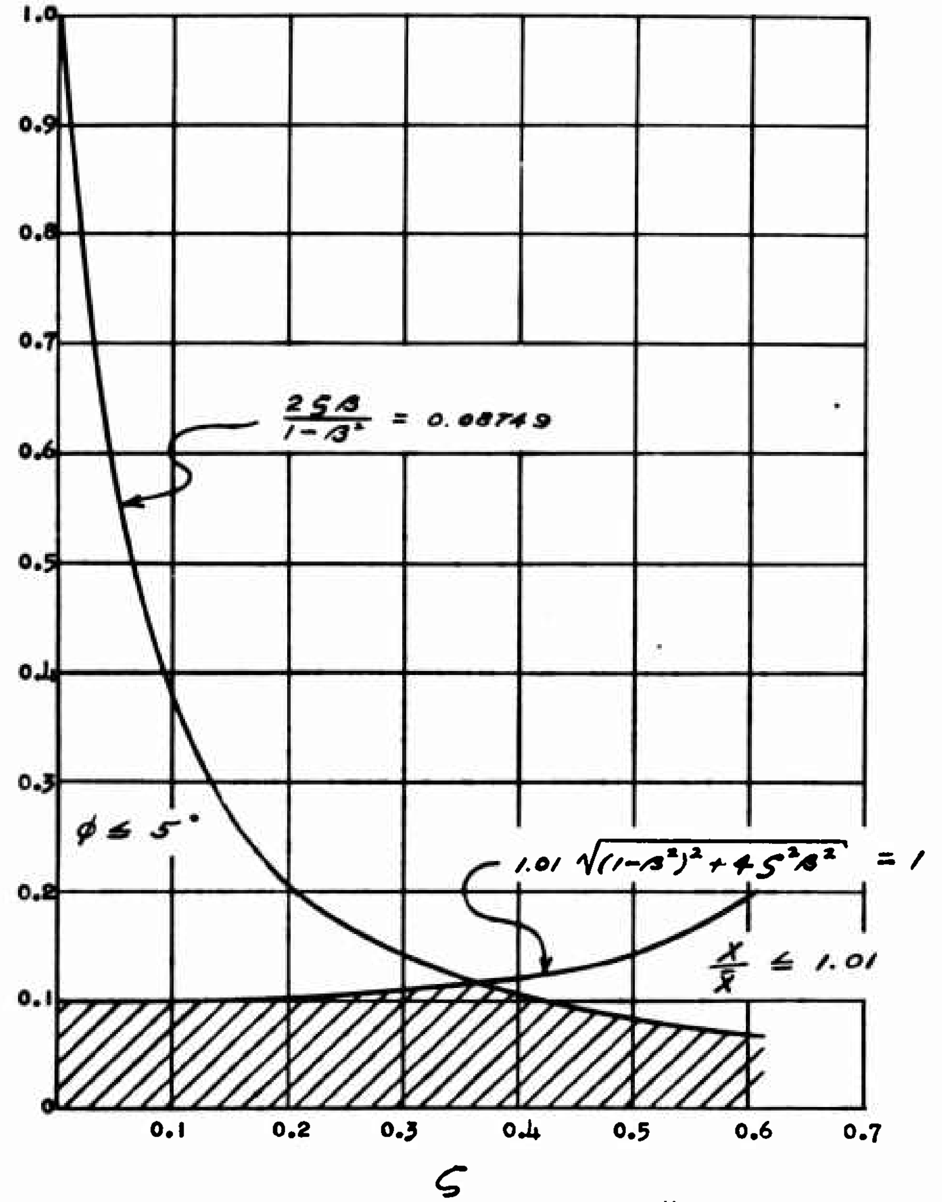
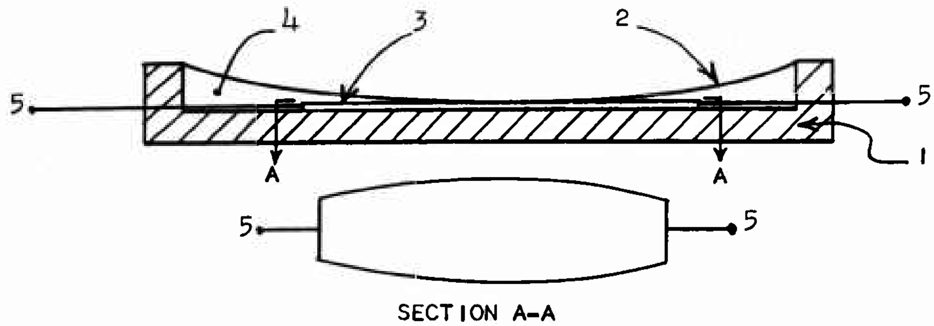


FIGURE 11. FREQUENCY RATIO - DAMPING RATIO ENVELOPE FOR $\frac{X}{\bar{X}} \leq 1.01$ AND $\phi \leq 5°$



1. Insulating Material
2. Metallic Diaphragm
3. Resistance Element Contoured to Obtain Linear Change in Resistance
4. Evacuated Chamber
5. To DC Power Supply and Readout Equipment

FIGURE 12. SCHEMATIC DIAGRAM OF DIAPHRAGM TYPE RESISTANCE-SHUNTING PRESSURE TRANSDUCER

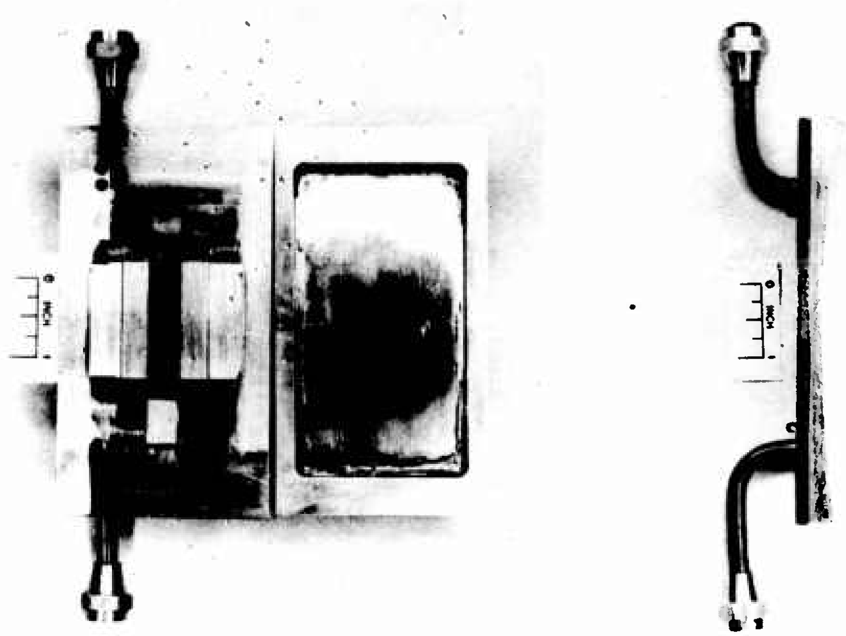


FIGURE 13. PHOTOGRAPH OF LABORATORY MODEL OF RESISTANCE-SHUNTING PRESSURE TRANSDUCER

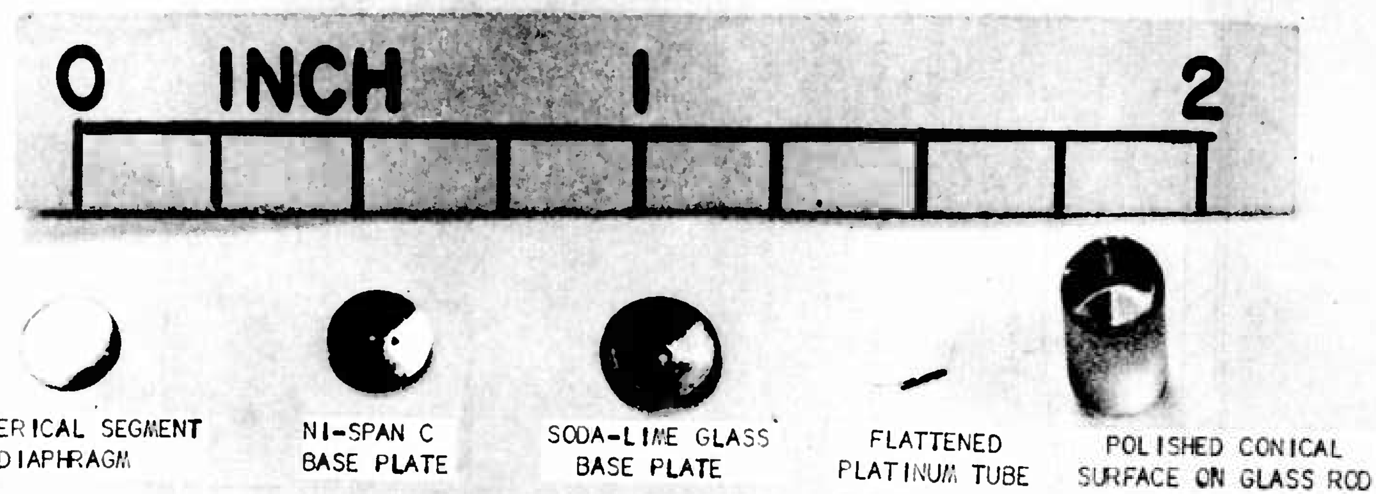


FIGURE 14. PHOTOGRAPH OF MINIATURE RESISTANCE-SHUNTING PRESSURE TRANSDUCER COMPONENTS

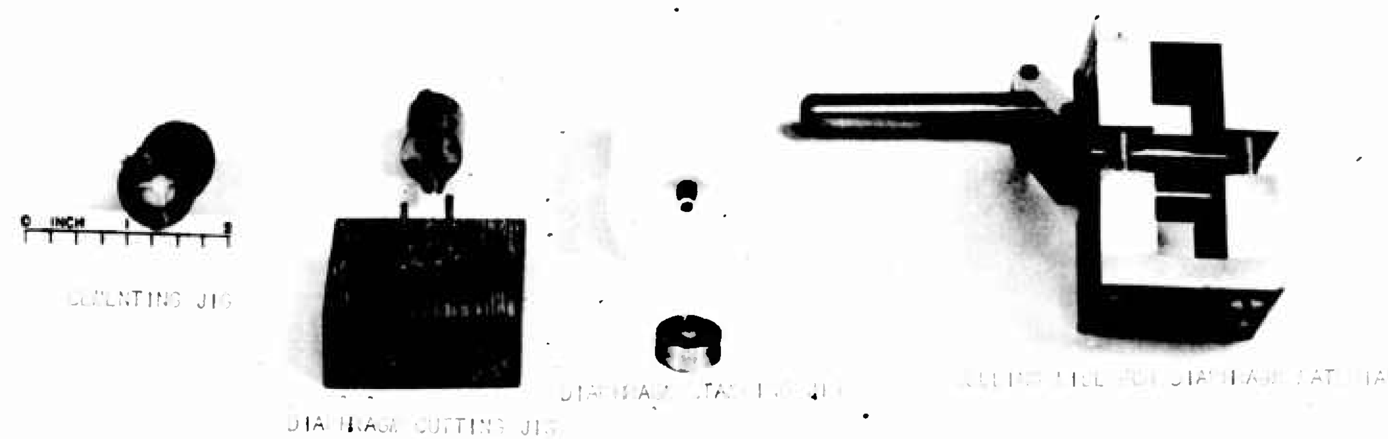
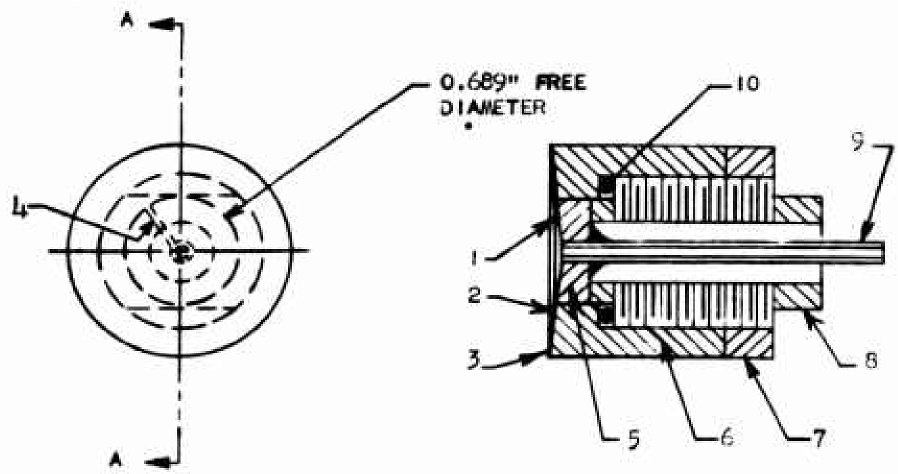


FIGURE 15. PHOTOGRAPH OF FABRICATION FIXTURES FOR THE MINIATURE RESISTANCE-SHUNTING PRESSURE TRANSDUCER



SECTION A-A

NOTES:

1. SPHERICAL DIAPHRAGM MADE OF 6 MIL BRASS SHIM STOCK. RADIUS OF CURVATURE IS 2.97"
2. ANGLE OF CONICAL TAPER IS 6.64°
3. DIAPHRAGM CEMENTED TO RIM WITH ARMSTRONG A-6 CEMENT
4. RESISTIVE FILM OF PLATINUM PAINT
5. FUSED QUARTZ BASE
6. THREADED DIAPHRAGM RIM
7. LOCK NUT
8. THREADED BRASS PLUG
9. 1/8" BRASS TUBE CEMENTED TO QUARTZ BASE FOR TRANSDUCER EVACUATION AND ELECTRICAL CONTACT TO THE RESISTIVE FILM BY USE OF INDIUM SOLDER
10. RUBBER "O"-RING

FIGURE 16. SCHEMATIC DIAGRAM OF THE SCALED-UP RESISTANCE-SHUNTING PRESSURE TRANSDUCER

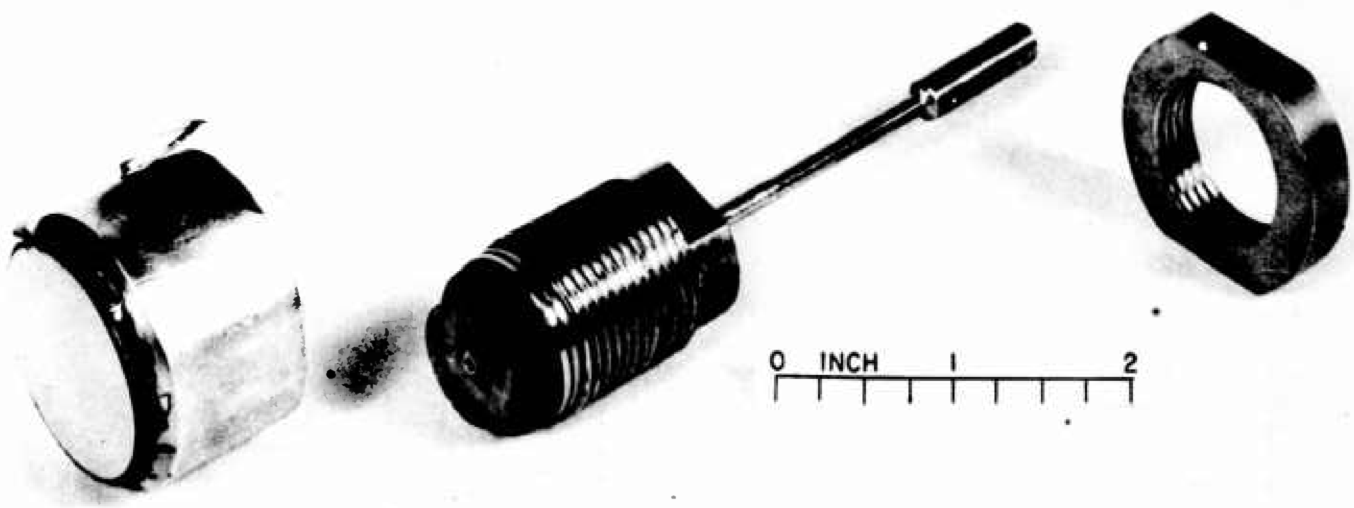


FIGURE 17. PHOTOGRAPH OF THE SCALED-UP RESISTANCE-SHUNTING PRESSURE TRANSDUCER

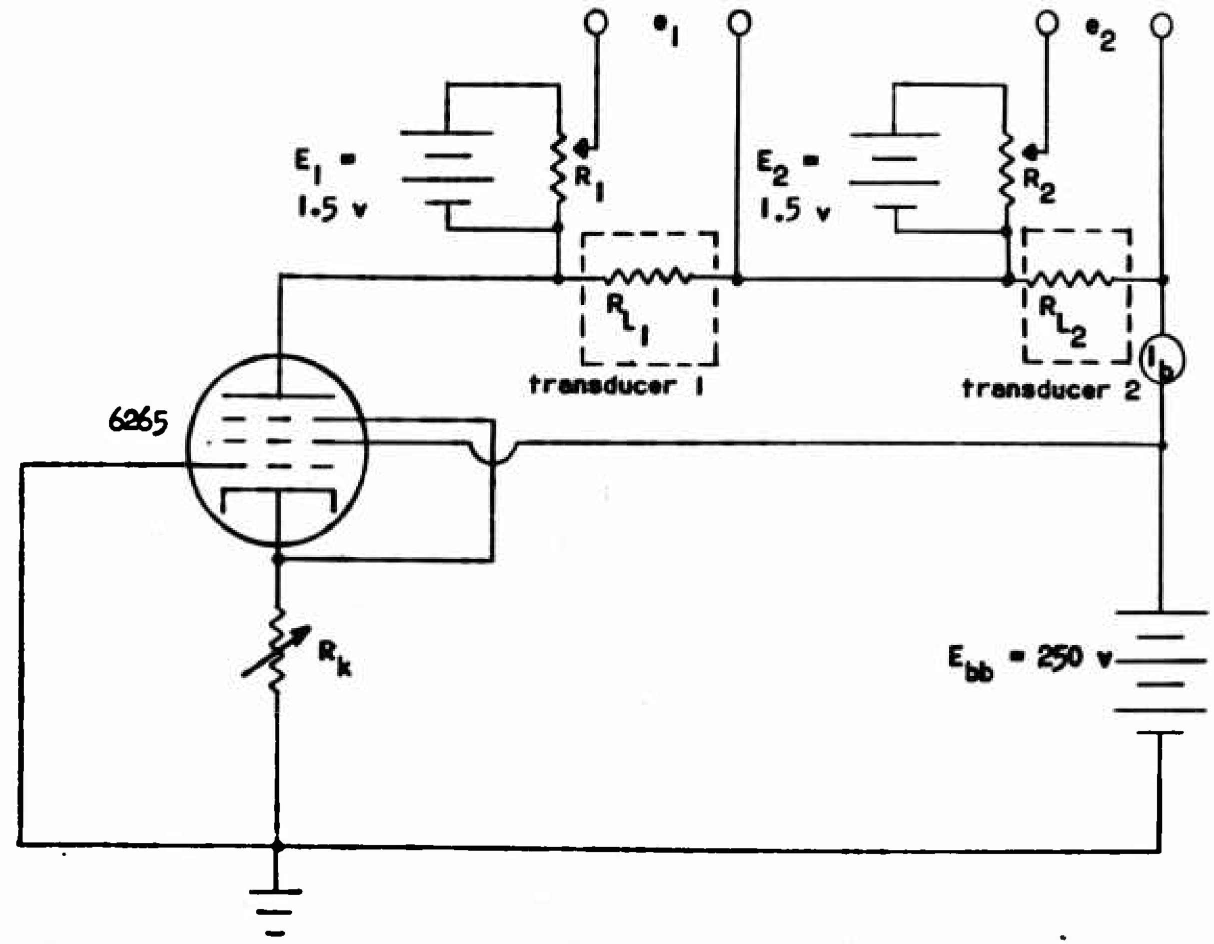


FIGURE 18. DETECTION CIRCUIT FOR RESISTANCE-SHUNTING PRESSURE TRANSDUCER

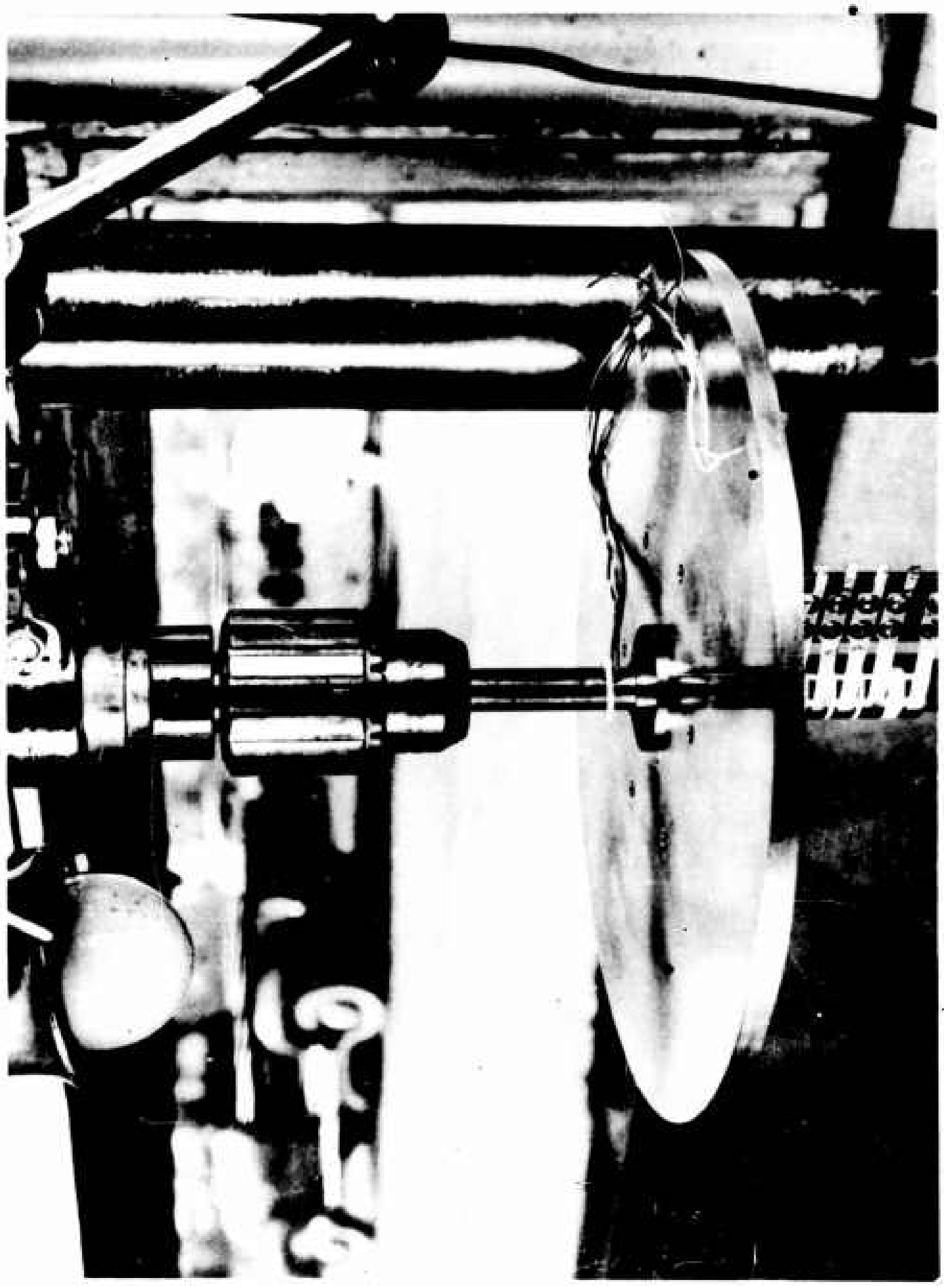


FIGURE 19. PHOTOGRAPH OF THE CENTRIFUGE

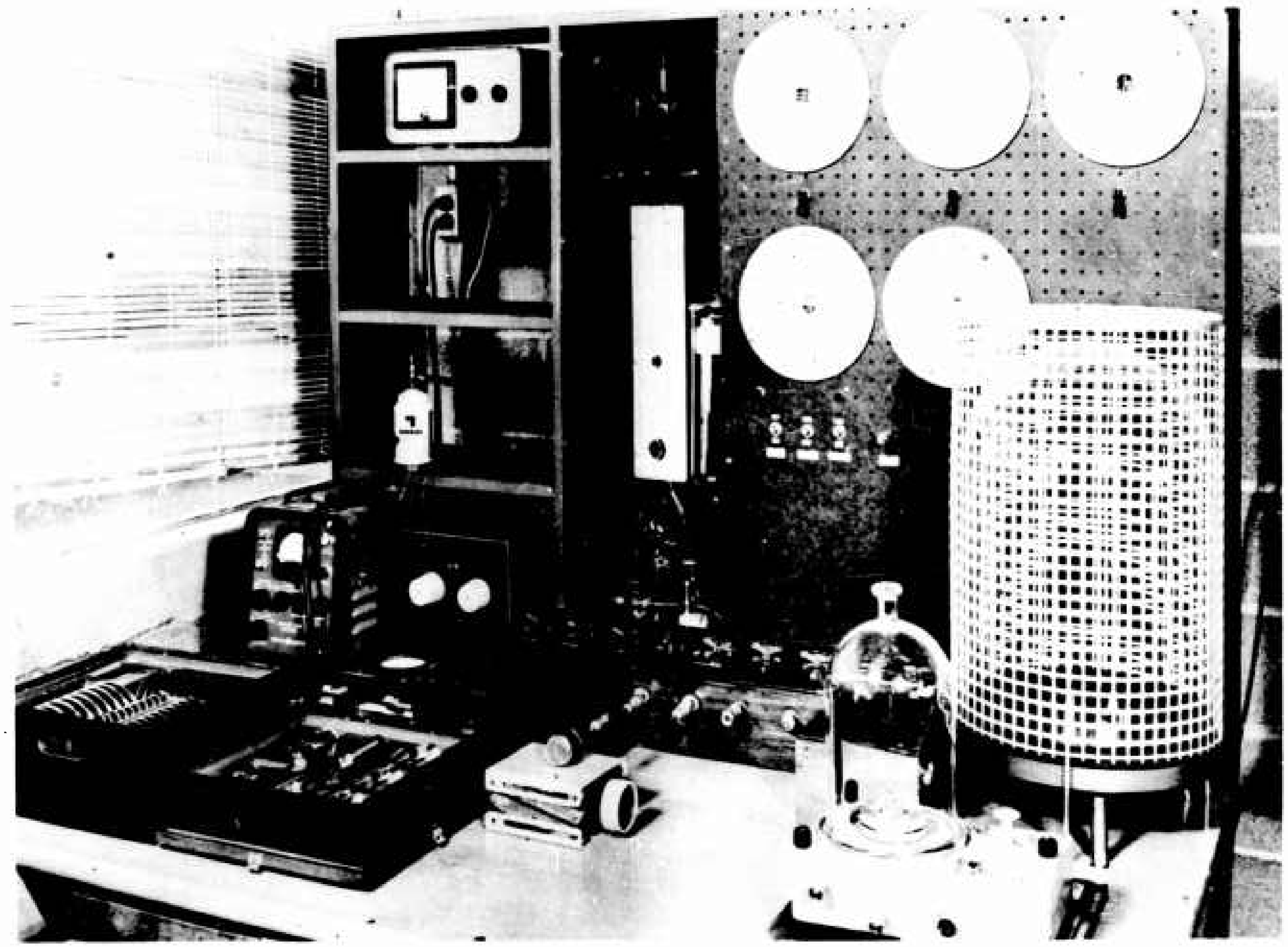


FIGURE 20. PHOTOGRAPH OF THE PRESSURE CALIBRATION FACILITY

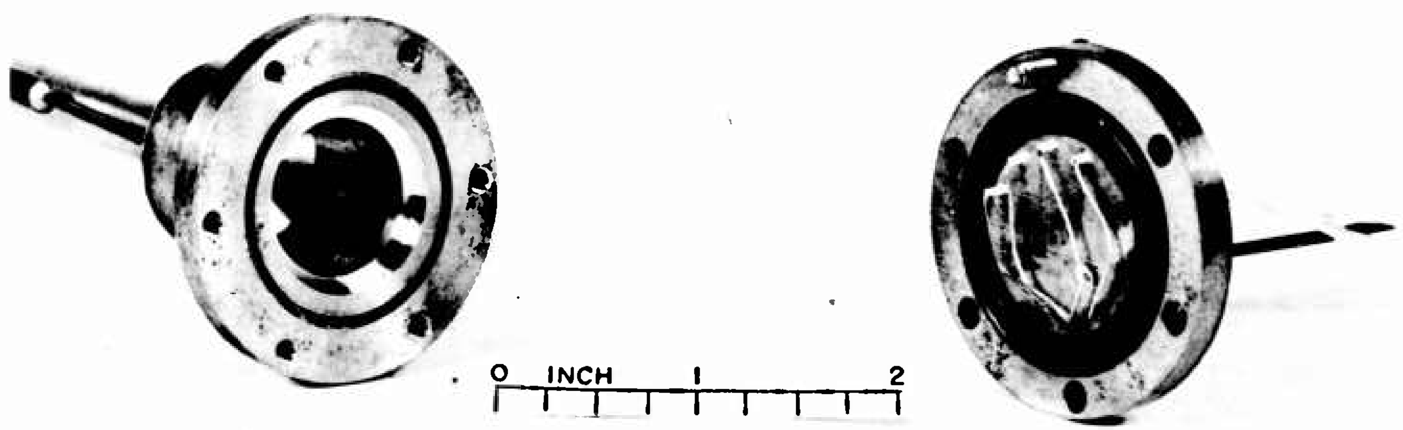


FIGURE 21. PHOTOGRAPH OF THE TEMPERATURE SENSITIVITY DETERMINATION APPARATUS

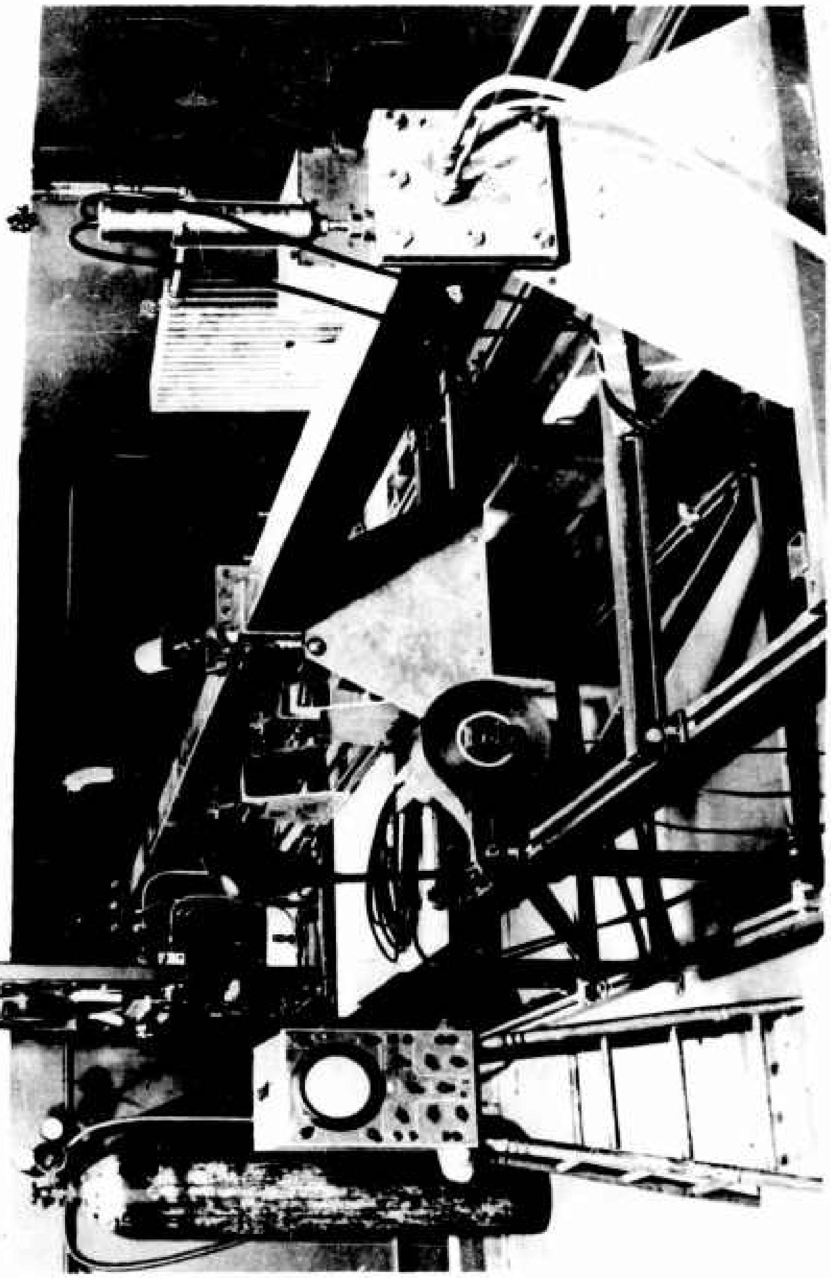


FIGURE 22. PHOTOGRAPH OF THE SHOCK TUBE

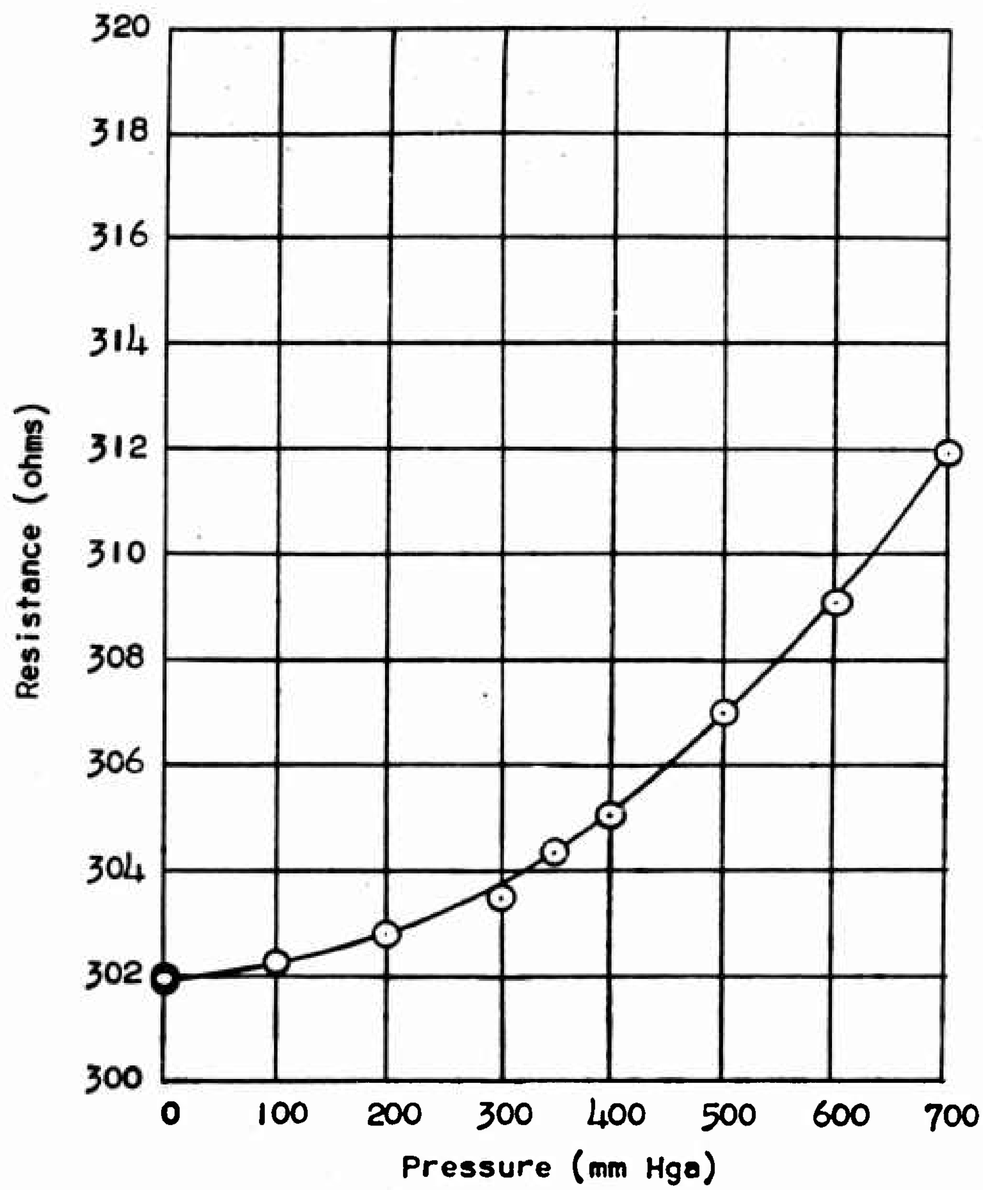


FIGURE 23. CALIBRATION OF THE SCALED-UP RESISTANCE-SHUNTING PRESSURE TRANSDUCER

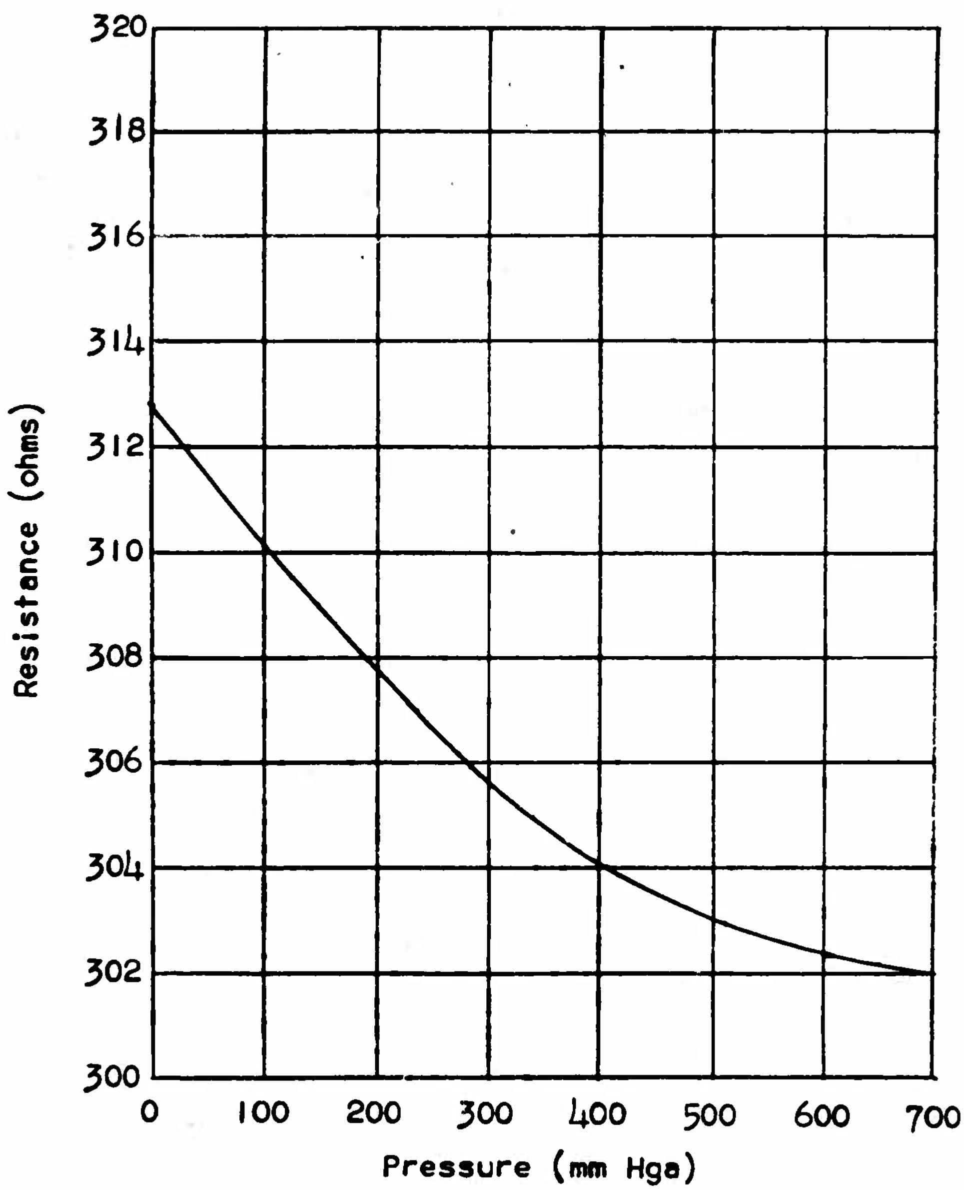


FIGURE 24. MODIFIED CALIBRATION CURVE FOR THE SCALED-UP RESISTANCE-SHUNTING PRESSURE TRANSDUCER

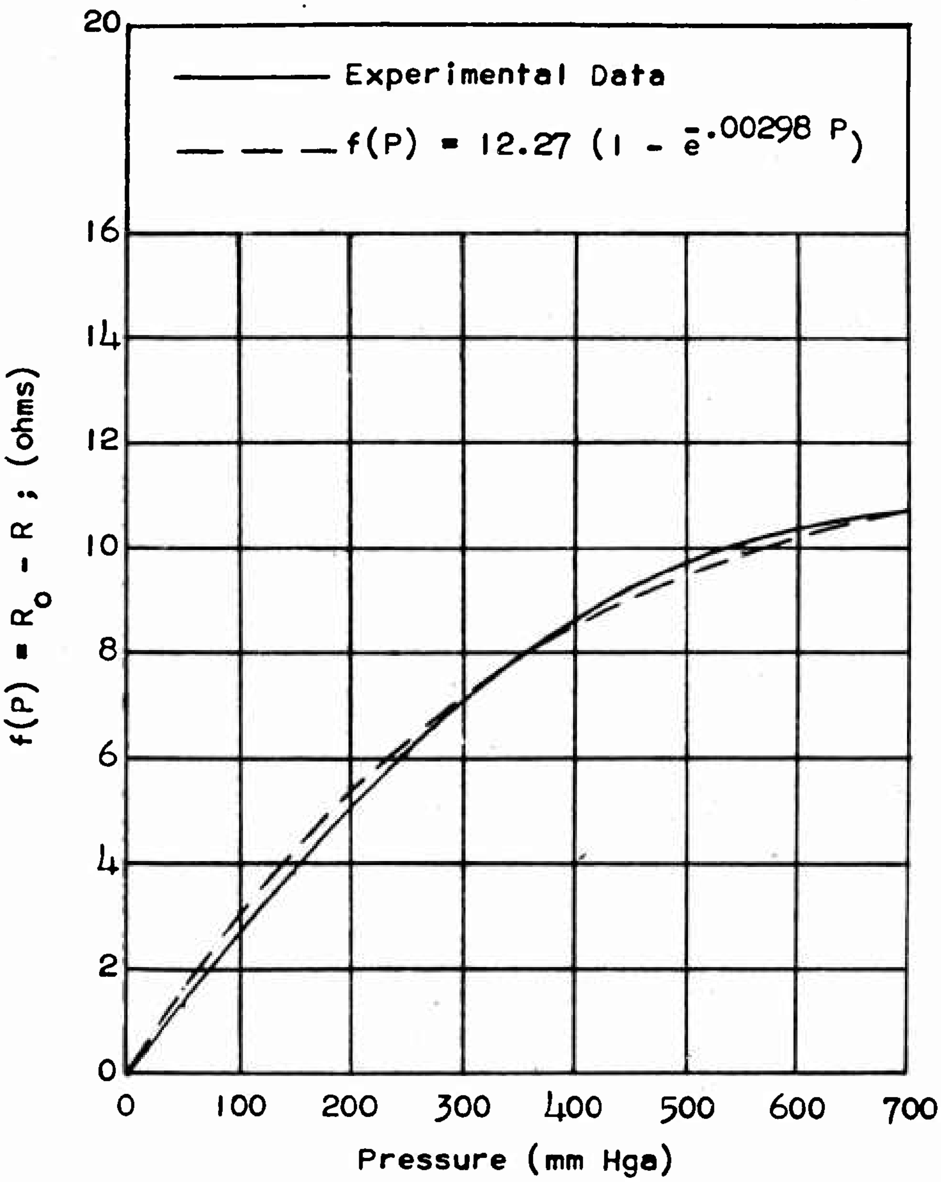


FIGURE 25. EXPERIMENTAL AND EMPIRICAL CURVES OF PRESSURE FUNCTION FOR THE SCALED-UP RESISTANCE-SHUNTING PRESSURE TRANSDUCER

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The problem of designing an accurate (over)

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3. Transducers, Instrumentation

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A design study of the diode principle for a miniature pressure transducer is presented. Details of the development of a variable resistance pressure transducer along with calibration data are also included.

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microminiature pressure transducer suitable for bonding to a vehicle surface exposed to a moving airstream has been reviewed in detail. A detailed discussion of newly evolved pressure-measuring techniques and adaptations considered feasible for the above application is given.

A design study of the diode principle for a miniature pressure transducer is presented. Details of the development of a variable resistance pressure transducer along with calibration data are also included.

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